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COMPREHENSIVE REVIEW

Integrating Ozone Pretreatment in Green Extraction Techniques for Bioactive Compounds From Agro-Industrial Residues

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ABSTRACT

The escalating challenges of agro-food waste management have driven research into sustainable extraction methodologies for efficient bioactive compound recovery. Conventional thermal and solvent-based methods often result in compound degradation, solvent toxicity, long extraction times, and low yields. In contrast, non-thermal strategies provide higher efficiency, reduced solvent use, shorter processing times, and better preservation of thermolabile compounds, enabling greener recovery processes. Ozone has emerged as an eco-friendly, non-thermal alternative with strong oxidative and cell-disruptive properties that enhance extraction performance. This review critically examines ozone's roles as pretreatment, direct extraction enhancer, and solvent activation agent in agro-food biomass valorization. Ozone facilitates cell wall disruption, mass transfer, and selective oxidation, improving recovery of polyphenols, flavonoids, carotenoids, and so forth. Furthermore, ozone modifies solvent polarity and reactivity, enhancing efficiency. Its integration with ultrasound, microwave, enzymatic, and supercritical fluid extractions offers promising potential for scalable, sustainable industrial applications. Unlike previous reviews, which mainly focused on ozone's lab-scale applications, this paper provides a novel and critical perspective by exploring ozone as a three-fold strategy. It uniquely discusses mechanistic insights and synergistic hybrid extractions and evaluates safety, environmental, and regulatory considerations that are often overlooked. While ozone-assisted extraction (OAE) technologies hold great potential, challenges such as compound stability, optimization of treatment parameters, and regulatory considerations require further exploration. This review highlights recent advancements in OAE and discusses industrial feasibility, economic concerns, and future research directions. By integrating ozone technology into bioactive compound recovery, agro-food waste valorization can contribute significantly in developing a circular economy and a more sustainable food industry.

1 | Introduction

The increasing concern over environmental sustainability and the urgent need for efficient resource utilization have led to significant interest in recovering bioactive compounds from agro-food industrial biomass. Agro-industrial by-products such as fruit peels, seeds, husks, cereal brans, and vegetable residues are rich in bioactive compounds, including polyphenols, flavonoids, carotenoids, and alkaloids, which possess potent antioxidant, anti-inflammatory, and antimicrobial properties. These bioactives hold immense commercial value in the functional food, nutraceutical, pharmaceutical, and cosmetic industries, promoting human health and offering potential therapeutic benefits. Efficiently extracting bioactive compounds from plant matrices remains challenging, primarily due to biomass structural complexity and the inherent limitations of traditional extraction methods (Anjali et al. 2024; Bhati et al. 2024). Conventional methods like thermal treatment, solvent extraction, and mechanical disruption frequently cause thermolabile compound degradation, high solvent usage, prolonged extraction times, and raise environmental toxicity concerns (Garofalo et al. 2022). Therefore, there is a pressing need for sustainable, non-thermal, and green extraction technologies that maximize bioactive compound recovery while minimizing environmental impact and ensuring economic feasibility (Çelebi et al. 2024; Kaur et al. 2022).

Among the emerging technologies, ozone has gained considerable attention as a promising green and non-thermal approach to enhance bioactive compound recovery. Ozone, a potent oxidizing agent, disrupts cell wall structures, increasing membrane permeability, facilitating mass transfer, and significantly improving the extraction efficiency of intracellular bioactive compounds (Epelle, Macflarane, et al. 2023; Lee et al. 2022). Ozone treatment operates without excessive thermal input, preserving heat-sensitive bioactives while altering plant matrix properties to enhance the accessibility and recovery of target compounds, unlike conventional methods dependent on heat or harmful solvents (Premjit et al. 2022). OSHA (Occupational Safety and Health Administration) states that an 8-h work shift average of 0.1 parts per million of ozone gas is the acceptable occupational exposure limit. By installing ambient air monitors with automated shutdown to stop leaks above permissible limits and using ozone-resistant materials, this exposure can be avoided. Maintain enough ventilation, give employees personal ozone detectors, and make sure all employees have received emergency response and ozone handling training (Rice 2012). This property is crucial for the food and nutraceutical sectors, where maintaining bioactive compound integrity is essential. Ozone enhances bioactive compound extraction via three principal mechanisms: (i) pretreatment, by disrupting plant cell wall structures to ease compound release; (ii) direct extraction enhancement, through selective oxidation of matrix-bound bioactives; and (iii) solvent activation, by modifying solvent polarity and reactivity to improve dissolution and extraction efficiency (Leeuwen et al. 2024; Shafiee and Samani 2024). These distinct but interconnected mechanisms make ozone a versatile tool for bioactive compound recovery from various agro-food industrial wastes.

Several studies have demonstrated ozone pretreatment's effectiveness in improving the extraction of bioactive compounds from fruit and vegetable by-products. Ozone exposure leads to the breakdown of lignocellulosic components, loosening the plant cell wall structure and increasing mass transfer efficiency (Gozé et al. 2017; Sachadyn-Król et al. 2016).

In wheat grains, ozone treatment has significantly altered protein and starch properties, leading to increased digestibility and enhanced bioactive availability. Typically, wheat grains are exposed to gaseous ozone at concentrations ranging from 50 to 80 mg/L for durations of 30–60 min under post-harvest storage conditions. This controlled exposure induces partial oxidation of starch granules and protein matrices, leading to their breakdown into simpler, more digestible forms. Moreover, the treatment promotes the release of bioactive compounds, including antioxidant phenolics and bioactive peptides, thereby enhancing the nutritional profile of wheat (Gozé et al. 2017). Similarly, the application of ozone in fruit peels and vegetable residues has resulted in higher polyphenol yields and improved antioxidant activity of extracts. Ozone can be applied through controlled gas exposure or in aqueous solutions to oxidize plant cell walls, breaking down lignin, cellulose, and hemicellulose. This disruption allows for easier extraction of polyphenolic compounds during subsequent processing. The enhanced antioxidant activity of the extracts indicates that ozone not only aids in the extraction process but also improves the bioavailability and efficacy of these bioactive compounds. This application has significant implications for the food and nutraceutical industries, where polyphenols are highly valued for their health benefits (Lee et al. 2022). Ozone's vital role in the direct extraction of bioactive compounds is particularly advantageous for compounds trapped within plant cell walls. The selective oxidation of these walls facilitates the release of bioactive compounds (such as phenolic acids), which are often bound in conjugated forms and are therefore less bioavailable (Çelebi et al. 2024; Epelle, Yaseen, et al. 2023). Moreover, ozone treatment has demonstrated its efficacy in improving the color stability and functional quality of carotenoid-rich extracts. Carotenoids, which are highly valued for their coloring and antioxidant properties, tend to degrade during processing and storage. By exposing carotenoid-rich plant materials to ozone, this treatment helps to stabilize the carotenoids by preventing their breakdown, thus maintaining both their color and antioxidant effectiveness. This makes ozone treatment particularly promising for applications in the food and cosmetic industries, where stable carotenoid extracts are in high demand for their aesthetic and health-promoting qualities (Premjit et al. 2022; Kaur et al. 2022). In addition, ozone has been investigated as a solvent activation agent, where its incorporation modifies solvent polarity and reactivity, leading to higher extraction yields, which is crucial for industries involved in essential oil (EO) extraction, polyphenol recovery, or other plant-based extractions. Ozone treatment optimizes the extraction process by altering the chemical properties of the solvent allowing for the recovery of a greater number of bioactive compounds in a more efficient manner (Shafiee and Samani 2024; Mamleeva et al. 2016). When paired with green solvents like ethanol, water, or supercritical CO_2, ozone treatment enhances extraction yields and reduces toxic solvent use, supporting sustainable food processing and aligning with green chemistry principles (Lee et al. 2022).

Ozone-based extraction can be effectively combined with green techniques like ultrasound, microwave, enzyme, and supercritical fluid extraction (SFE) for higher effectiveness (Panigrahi et al. 2023). Studies have shown that combining ozone with ultrasound results in enhanced cavitation effects, leading to improved mass transfer and increased extraction efficiency of polyphenols and flavonoids (Çelebi et al. 2024; Floare et al. 2023; Epelle, Yaseen, et al. 2023). Similarly, microwave-assisted extraction (MAE) benefits from ozone-induced structural modifications, which allow for better penetration of microwave energy and improved bioactive release (Huang et al. 2024). Ozone pretreatment can also enhance enzyme-assisted extraction (EAE), as ozone-mediated oxidative modifications make cell wall components more susceptible to enzymatic degradation (D. Zhang et al. 2022; C. Zhang et al. 2024). These hybrid extraction systems hold significant promise for industrial applications, offering improved extraction yields, reduced processing times, and lower environmental impact than traditional methods.

Despite the numerous benefits of ozone-assisted bioactive compound extraction, several challenges hinder its widespread implementation. A primary concern is the stability of ozone-treated bioactives, as excessive oxidation can lead to structural degradation and loss of functionality (Nickhil et al. 2022; Gozé et al. 2017; Kaur et al. 2022). To maximize extraction efficiency while maintaining bioactive integrity, optimization of ozone treatment parameters such as concentration, exposure time, and processing conditions is crucial. Additionally, the scalability of ozone-based extraction systems for industrial use requires further investigation, particularly in designing efficient ozone reactors and optimizing process economics (Epelle, Macflarane, et al. 2023; Shafiee and Samani 2024). Regulatory concerns also need attention, as its application in bioactive extraction lacks comprehensive guidelines, despite its approval as a generally recognized as safe (GRAS) substance for food decontamination and water treatment (Bhati et al. 2024; Epelle, Yaseen, et al. 2023). Integrating ozone with other green extraction techniques enhances its potential, offering a sustainable, eco-friendly, and economically viable approach to agro-food biomass valorization (Shafiee and Samani 2024; Kaur et al. 2022).

Recent reviews have highlighted numerous green and emerging extraction technologies, such as supercritical fluid, ultrasound, microwave, and enzymes, for bioactive compound recovery from agro-food waste. Afraz et al. (2023) assessed subcritical and SFE for fruit and vegetable waste valorization, emphasizing low-temperature, solvent-free techniques. While these methods reduce thermal degradation, their high-pressure requirements and costly equipment limit industrial scalability. While some studies, including Kaur et al. (2022) and Shafiee and Samani (2024), examined its effect on bioactive release from food and medicinal plants, they did not fully explore its role in solvent activation, mass transfer enhancement, or its industrial feasibility. There is a need for a more comprehensive understanding of ozone's mechanisms in bioactive compound extraction from plant matrices.

The present review differs significantly from previous works by providing a critical and novel perspective on ozone as a three-fold strategy for bioactive compound recovery as a pretreatment agent, a direct extraction enhancer, and a solvent activation catalyst. Unlike previous studies, this paper delves into the mechanistic insights of its interaction with plant matrices, its oxidative effects on solvent reactivity, and its synergy with advanced green extraction technologies. Additionally, the review highlights the potential of hybrid extraction approaches, combining ozone with ultrasound, microwave, enzyme, and supercritical fluid, to achieve superior bioactive yields. Previous works primarily discussed ozone's lab-scale applications without addressing its safety, environmental impact, and regulatory concerns, but this review critically evaluates the safety and regulatory matters. Beyond addressing existing research gaps, this review highlights ozone-assisted extraction's (OAE) broader impact. Scientifically, it advances understanding of its multifunctional role combined with green technologies. Industrially, it provides insights for developing scalable, efficient, and sustainable extraction processes for high-value food products. However, societally, it promoted agro-food waste valorization and environmental and sustainable economy practices, contributing to eco-friendly innovations. It explores its mechanisms, advantages over conventional methods, industrial feasibility, and future research directions, promoting agro-food waste valorization and eco-friendly bioactive recovery strategies.

2 | Fundamentals of Ozone in Food Processing

Ozone (O_3) is a highly reactive oxidizing agent widely applied in the food industry for its broad-spectrum antimicrobial properties and ability to degrade organic pollutants (Bhati et al. 2024; Brodowska et al. 2018). It enhances bioactive compound extraction as a solvent activator and non-thermal pre-treatment method. As an eco-friendly alternative to conventional disinfectants, ozone decomposes into oxygen (O_2) without leaving hazardous residues, making it ideal for food applications (Leeuwen et al. 2024). Ozone is referred to be an environmentally friendly technology in the food processing industry because it naturally breaks down to oxygen, leaving no toxic chemical residues and eliminating the need for chlorine-based sanitizers that can produce toxic by-products like trihalomethanes. It can be produced locally, removing the dangers that hazardous chemical storage and transportation provide to the environment. On the other hand, local air quality may be impacted and ground-level ozone pollution may result from the direct discharge of excess ozone into the atmosphere. OSHA has established stringent exposure limits for ozone, a potent oxidizing gas, from the standpoint of worker safety (0.1 ppm over 8 hours). Higher quantities of ozone can irritate the eyes, nose, throat, and lungs when inhaled, and longer exposure can result in more severe respiratory problems. Use of ozone-resistant materials, installation of ambient air monitors with automated shutdown mechanisms, enough ventilation, provision of personal ozone detectors and suitable personal protective equipment, and training of employees in leak detection, safe handling, and emergency response are all ways that food facilities can protect their employees. Its uses span decontamination, shelf-life extension, wastewater treatment, and bioactive compound recovery from agro-food biomass (Jafari and Therdthai 2022). Understanding its chemical properties, mechanisms, and regulatory aspects is crucial for optimizing its efficacy in food systems.

2.1 | Chemical Properties and Reactivity of Ozone

Industrial ozone is generated via corona discharge, ultraviolet (UV) radiation (185 nm), or electrolysis. Corona discharge, the most common method, produces ozone by splitting oxygen molecules using high-voltage electricity (Meher et al. 2023). When two specific electrodes, one acting as the ground electrode and the other as the dielectric (current-bearing) medium, pass through an oxygen-containing atmosphere under a high-energy electrical field, the electrical field causes oxygen molecules to split apart, creating extremely active atomic oxygen radicals that can join intact oxygen molecules to create molecular ozone.

UV lamps that can produce ozone have a target wavelength of 185 nm. The high-energy UV185 irradiance field surrounding the lamp allows feed gas, typically ambient air, to pass through. A tiny portion of oxygen molecules (O_2) splits through photo disassociation, producing unstable oxygen radical atoms (O_1). O_1 radical atoms easily cling to nearby O_2 molecules in search of stability, creating O_3 molecules, or ozone. By electrolyzing water with electrodes that separate its molecules into hydrogen and oxygen, ozone can be created. Ozone (O_3) is created when some of the oxygen produced at the anode undergoes further oxidation under specific circumstances (K. Zhang et al. 2025)

Ozone, an allotrope of oxygen, has a bent molecular structure with a high redox potential (+2.07 V), making it a potent oxidizing agent (Premjit et al. 2022). It reacts with proteins, lipids, and nucleic acids, leading to microbial inactivation and degradation of organic matter. Ozone's electrophilic nature targets electron-rich biomolecules such as amines, thiols, and double bonds, altering their structure through oxidation (Bhati et al. 2024). This property is valuable in food processing, improving bioactive compound extraction, contaminant removal, and pathogen inactivation. Table 1 details the primary and secondary oxidants created throughout the ozonation procedure, which drive diverse food processing reactions.

Environmental factors like temperature, pH, and organic matter influence ozone's effectiveness. In water, it decomposes rapidly, generating reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2), superoxide anions ($O_2\cdot^-$), and hydroxyl radicals (·OH), which further enhance oxidation processes (Brodowska et al. 2018). Hydroxyl radicals, with a redox potential of +2.8 V, accelerate organic molecule oxidation and microbial cell destruction (Bhati et al. 2024). Ozone's half-life in water ranges from seconds to minutes, depending on pH, temperature, and dissolved organic matter levels (Premjit et al. 2022). Its versatile oxidative mechanisms position the ozone as a promising tool for sustainable food processing and enhanced bioactive compound recovery (Anjali et al. 2024; Pérez-Andrés, Charoux, Cullen, and Tiwari 2018). Ozone's solubility in water influences its oxidative performance, with better solubility in cold water enhancing its efficacy (Epelle, Yaseen, et al. 2023). Its oxidation occurs via direct molecular interactions or indirect radical-mediated reactions, both enhancing bioactive compound extraction and solvent activation (Shafiee and Samani 2024).

2.2 | Mechanism of Ozone Action in Organic Matter Degradation and Cell Wall Disruption

Ozone's strong oxidative properties alter the structure and function of organic matter, including food components and plant tissues, leading to cell wall disruption in both plant and microbial cells. This dual effect not only inactivates microorganisms, thereby reducing enzymatic degradation of target compounds, but also enhances bioactive compound extraction by increasing cell permeability and modifying plant tissue matrices (Brodowska et al. 2018; Kaur et al. 2022). Through direct oxidation and radical-mediated reactions, ozone interacts with biomolecules, causing structural breakdown and promoting the release of intracellular compounds (Jafari and Therdthai 2022). However, some primary and secondary chemical reactions occurred due to ozone oxidation during various food processing steps as shown in Table 2.

2.2.1 | Ozone-Induced Oxidation of Biomolecules

Ozone directly impacts many biomolecules, which alter their structural integrity and functionality. Environmental factors and molecular composition influence the oxidation process's different paths. One of the primary mechanisms involves the disruption of carbon–carbon double bonds found in unsaturated fatty acids, phenolic compounds, and other organic structures (Bhati et al. 2024; Brodowska et al. 2018). When ozone combines with electron-rich sites, aldehydes, ketones, peroxides, and ozonides are created. It creates lipid hydroperoxides by oxidizing unsaturated fatty acids in cell membranes. Membrane instability caused by these intermediates results in oxidative damage and the production of secondary oxidation products, such as malondialdehyde (Çelebi et al. 2024). Phospholipid oxidation compromises membrane integrity, increasing permeability and causing intracellular leakage, facilitating plant cell disruption and microbial inactivation, and enhancing extraction and preservation processes. As a result, the release of bioactive compounds is enhanced, and solvent penetration becomes more efficient, improving extraction processes (Çelebi et al. 2024).

Ozone (O_3) is a potent oxidant that interacts with proteins by generating ROS such as singlet oxygen ($^1O_2$) and hydroxyl radicals (−OH). These ROS primarily target specific amino acid side chains, including sulfur-containing residues (cysteine and methionine), aromatic residues (tryptophan, tyrosine, and phenylalanine), and amine groups in lysine and histidine. Cysteine's thiol (−SH) group is particularly vulnerable to oxidation, leading to the formation of disulfide bonds or sulfenic acid derivatives. Methionine undergoes oxidation to form methionine sulfoxide. Aromatic residues like tryptophan are oxidized to kynurenine, while tyrosine forms ortho-quinones. Lysine and histidine, with their amino groups, can be modified into carbonyl derivatives such as Nε-carboxymethyl-lysine (CML), impairing protein function (Gozé et al. 2017). These oxidative modifications can lead to several detrimental consequences. One of the major outcomes is peptide fragmentation where the oxidation weakens

TABLE 1 | List of primary and secondary oxidants generated during the ozonation process along with their respective function.

Type of oxidants	Oxidant	Chemical symbol	Reaction equation	Function	References
Primary oxidant	Ozone	O_3	$O_3 + e^- \rightarrow O_2 + O\bullet$	Direct oxidation of organic and inorganic compounds, microbial inactivation	Meher et al. (2023)
	Singlet oxygen	$^1O_2$	$O_3 + H_2O \rightarrow {}^1O_2 + 2\ \bullet OH$	Reacts with unsaturated bonds in organic molecules, leading to oxidation	Premjit et al. (2022)
	Atomic oxygen	$O\bullet$	$O_3 \rightarrow O_2 + O\bullet$	Highly reactive, it breaks molecular structures through oxidation	Greene et al. (2012)
Secondary oxidant	Hydroxyl radicals	$\bullet OH$	$O_3 + H_2O \rightarrow \bullet OH + HO_2\bullet$	Extremely reactive, non-selective oxidant that enhances organic degradation	Dai et al. (2024)
	Superoxide anions	$O_2\bullet^-$	$O_3 + e^- \rightarrow O_2 + O_2\bullet^-$	Intermediate radicals in oxidation reactions contribute to radical chain reactions	Wei et al. (2017)
	Hydrogen peroxide	H_2O_2	$O_3 + H_2O_2 \rightarrow O_2 + 2\ \bullet OH$	Participates in oxidative reactions and enhances ozone efficiency	O'Donnell et al. (2012)
	Peroxyl radicals	$ROO\bullet$	$RH + O_2 \rightarrow R\bullet + ROO\bullet$	Involved in lipid oxidation, promoting membrane disruption	Brodowska et al. (2018)
	Ozonides	O_3^-	$O_3 + O_2\bullet^- \rightarrow O_3^- + O_2$	Unstable intermediates that propagate oxidation reactions	Dai et al. (2024)

TABLE 2 | List of primary and secondary chemical reactions during events in food processing.

Events	Type of reaction	Primary chemical reaction	Secondary chemical reaction	References
Microbial inactivation	Oxidation of cell membranes	O_3 + lipids → lipid peroxides → cell lysis	$O_3 + H_2O \rightarrow \bullet OH + O_2\bullet^- + H_2O_2$ (ROS formation)	Brodowska et al. (2017)
Protein modification	Oxidation of thiol groups	O_3 + R-SH → R-S-S-R (disulfide bonds)	$O_3 + H_2O_2 \rightarrow \bullet OH$ + oxidized amino acids	Pérez-Andrés et al. (2018)
Lipid oxidation	Cleavage of double bonds	$O_3 + C = C \rightarrow$ aldehydes + ketones	Lipid peroxidation → hydroperoxides (LOOH) → radicals (LO•, LOO•)	Çelebi et al. (2024); Pérez-Andrés et al. (2018)
Nucleic acid disintegration	Oxidation of nitrogenous bases	O_3 + guanine → 8-oxo-guanine (mutagenic effect)	$O_3 + O_2\bullet^- \rightarrow ONOO^-$ (peroxynitrite formation)	Sharma and Graham 2010
Polysaccharide degradation	Breakdown of cell wall components	O_3 + cellulose → oxidized oligosaccharides	$O_3 + \bullet OH \rightarrow$ oxidative depolymerization	Mamleeva et al. (2016); Mzoughi et al. (2017)
Bioactive compound extraction	Disruption of organic matrices	O_3 + phenolic structures → enhanced solubility	ROS-mediated structural modifications (hydroxylation, cleavage)	Brodowska et al. (2015); Sachadyn-Król et al. (2016)
Water treatment and purification	Oxidation of organic/inorganic contaminants	O_3 + pollutants → oxidized by-products	$O_3 + Cl^- \rightarrow ClO_2\bullet$ (chlorine dioxide) + other reactive halogen species	Hai et al. (2018)
Aqueous decomposition	Formation of ROS	$O_3 + H_2O \rightarrow \bullet OH + O_2\bullet^- + H_2O_2$	Radical chain reactions producing highly oxidative intermediates	Hai et al. (2018); Wei et al. (2017)

peptide bonds resulting in smaller peptides or free amino acids, which further destabilize protein structure and function. Additionally, protein aggregation occurs as disulfide bonds or other cross-linking modifications promote the formation of insoluble aggregates. This aggregation disrupts cellular processes and can contribute to diseases caused by protein misfolding. Another consequence of oxidation is the formation of new disulfide bonds between cysteine residues, which can lock proteins into incorrect conformations and impair their function, particularly in enzymes that rely on precise folding for activity (Çelebi et al. 2024).

Ozone-induced oxidation also destabilizes cellular integrity by affecting both metabolic and structural proteins. The key enzymes involved in metabolic pathways (such as kinases and phosphatases) may lose activity due to oxidation, which leads to metabolic instability. This can affect cellular homeostasis and disrupt critical processes like energy production and signaling. Oxidation also affects structural proteins like collagen and actin, compromising cell membrane integrity and mechanical strength, particularly in tissues like connective tissue and muscle. This destabilization can cause further cellular dysfunction. Oxidative damage to proteins triggers inflammatory responses and may lead to cell death. The damaged proteins can signal the immune system activating inflammatory pathways and contributing to conditions such as Alzheimer's, Parkinson's, and cystic fibrosis. Oxidative modifications also interfere with signal transduction pathways by altering the function of receptors and signaling molecules, which can disrupt cellular communication and affect processes like growth, differentiation, and immune responses (Gozé et al. 2017). Overall, ozone-induced protein oxidation leads to a cascade of structural and functional alterations, destabilizing cellular processes, impairing protein function, and contributing to diseases associated with oxidative stress and protein damage. Conversely, polysaccharides, which serve as the primary structural component of plant cell walls, undergo oxidative depolymerization upon exposure to ozone. The cleavage of glycosidic bonds breaks down cellulose and hemicellulose, while ozone-induced oxidation disintegrates the cross-linked polymeric structure of lignin (Mamleeva et al. 2016; Mzoughi et al. 2017). Changing these structural components makes the cell wall more permeable, facilitating the extraction of intracellular materials like polyphenols, flavonoids, and carotenoids (Mamleeva et al. 2016).

2.2.2 | Ozone-Induced Cell Wall Disruption for Bioactive Compound Extraction

Building on the cell wall disruption mechanisms described in Section 2.2.1, ozone has been effectively applied as a pre-treatment to enhance the recovery of bioactive compounds from plant-based foods. By loosening the lignocellulosic matrix and increasing cell wall porosity, ozone facilitates solvent penetration and the release of intracellular phytochemicals without the need for harsh solvents or high temperatures (Brodowska et al. 2015; Jafari and Therdthai 2022).

This approach is particularly valuable for compounds sensitive to thermal degradation, such as carotenoids (e.g., lutein, lycopene, β-carotene), which diffuse more readily into extraction solvents while retaining structural integrity (Lee et al. 2022; Gutierrez et al. 2018). However, since carotenoids are also highly susceptible to oxidative cleavage, careful control of ozone concentration and exposure time is essential to maximize recovery while minimizing oxidative losses. Ozone pre-treatment also improves the liberation of alkaloids (e.g., caffeine, theobromine, capsaicinoids) and terpenoids, thereby enhancing both the yield and quality of extracts (Gutierrez et al. 2018; Sachadyn-Krol et al. 2016). The combined effect of ozone's direct oxidation and secondary oxidants, such as hydroxyl radicals (•OH), ozonides, and peroxides, accelerates oxidative depolymerization of cell wall polysaccharides and other structural components. This results in substantial matrix disintegration, increased cell membrane permeability, and faster release of intracellular constituents. Furthermore, ozone modifies the physical properties of the extraction medium by reducing surface tension and altering solvent polarity, thereby improving solvent penetration into plant tissues. These combined effects enhance mass transfer, reduce extraction time, and support greener processing by minimizing chemical inputs.

A schematic representation of the extraction of bioactive compounds from foods using OAE is shown in Figure 1.

2.2.3 | Hydroxyl Radical Formation and Secondary Oxidation Reactions

Ozone breaks down in aqueous systems to produce hydroxyl radicals (•OH), which are among the most ROS and have a higher oxidation potential than ozone itself. The following equations illustrate how these radicals are created by chain reactions involving hydrogen peroxide (H2O_2), superoxide anions (O_2•$^-$), and ozone (O_3; Meher et al. 2023). Hydroxyl radicals are essential in food processing and the extraction of bioactive compounds because of their high reactivity, which allows them to disintegrate complex organic molecules that might be resistant to direct ozone oxidation (Greene et al. 2012; Premjit et al. 2022). The reaction pathway begins with ozone reacting with water to form hydroxyl radicals:

$$O_3 + H_2O \rightarrow 2{\bullet}OH + O_2O_3 + H_2O \rightarrow 2{\bullet}OH + O_2O_3 + H_2O \rightarrow 2{\bullet}OH + O_2 \quad (1)$$

Additionally, superoxide anions (O_2•$^-$) generated during ozone decomposition further influence radical formation:

$$O_2{\bullet}- + O_3 \rightarrow O_2 + O_2{\bullet} + {\bullet}OHO_2{\bullet}- + O_3 \rightarrow O_2 + O_2{\bullet} + {\bullet}OHO_2{\bullet}- + O_3 \rightarrow O_2 + O_2{\bullet} + {\bullet}OH \quad (2)$$

Moreover, by encouraging their breakdown, hydroxyl radicals enhance the extraction of phenolic compounds, flavonoids, carotenoids, and alkaloids from plant matrices. The oxidation of cell wall components facilitates the release of intracellular bioactive compounds and improves solvent penetration (Lee et al. 2022; Sachadyn-Król et al. 2016). This mechanism supports sustainable extraction by reducing harsh chemicals and heat use, but excessive oxidation may initiate radical activity, degrading or altering essential bioactive compounds (Brodowska et al. 2015). Additionally, prolonged hydroxyl radical exposure

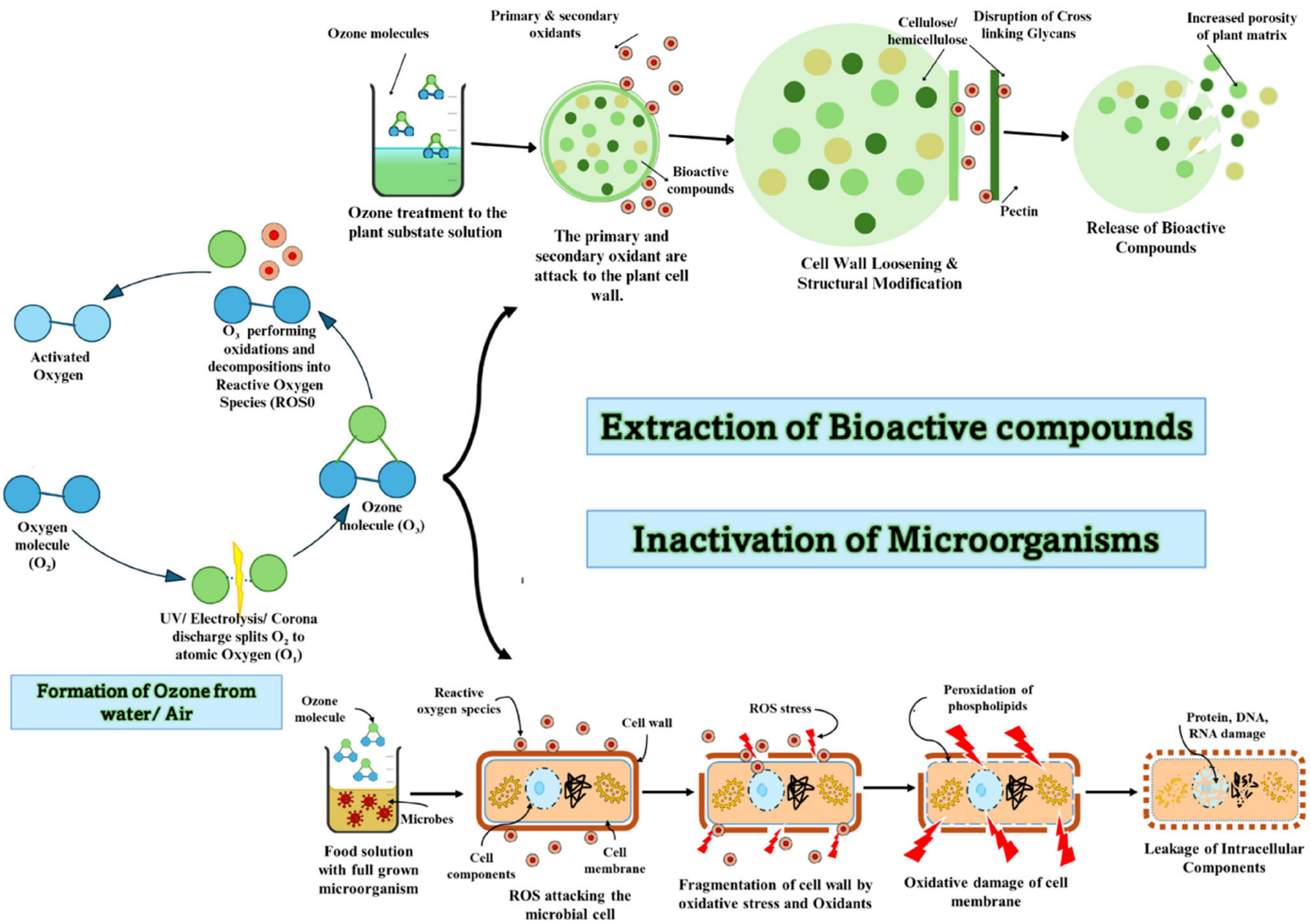

FIGURE 1 | Graphical representation of the mechanism of inactivation/ killing of the microorganisms in foods subjected to the ozone pre-treatment.

can reduce flavonoid antioxidant potential; therefore, optimizing ozone concentration, exposure time, pH, and temperature is crucial to maximize recovery while minimizing their oxidative damage (Gutierrez et al. 2018; Shafiee and Samani 2024). By carefully controlling hydroxyl radicals, ozone treatment suggests a sustainable and efficient method to improve the extraction and functionality of bioactive compounds in food, pharmaceutical, and nutraceutical applications.

3 | Ozone as a Non-Thermal Pretreatment for Bioactive Extraction

Ozone is a non-thermal pretreatment that preserves heat-sensitive compounds, maintaining food's nutritional value and sensory qualities by avoiding thermal degradation. However, due to its strong oxidative nature, improper control of concentration and exposure time can lead to oxidation of pigments and other sensitive components, potentially altering sensory properties such as color and flavor. Figure 2 represents the detailed experimental setup and mechanisms involved in ozone pre-treatment of fruits and vegetables. Ozone acts as a strong chemical disinfectant and preservative agent in food processing based on its characteristics and minimizes the environmental impact (Niveditha et al. 2021). The effectiveness of this method depends on multiple factors, including ozone concentration, exposure time, food type, processing conditions, temperature, humidity, delivery system design, and adherence to safety protocols (Wei et al. 2017). Proper regulation of these parameters is essential to preserve food quality and bioactive compounds. Due to ozone's high reactivity, handling precautions and protective equipment are necessary to prevent direct exposure and respiratory risks, ensuring safe and effective application (Prabha et al. 2015). According to OSHA, the permissible occupational exposure limit for ozone gas is 0.1 parts per million, averaged over an 8-h work shift. The following section discusses the effects of ozone pretreatment on bioactive compound extraction from various fruit and vegetable sources.

3.1 | The Effect of Ozone on the Bioactive Components of Food

i) **Polyphenols**

Ozone pre-treatment enhances polyphenol levels by increasing ROS and enzyme activity, which can improve the antioxidant profile of the product mainly in post-harvest fruits and vegetables, including produce like tomatoes, grapes, berries, lettuce, and spinach. However, polyphenol oxidase (PPO) activation forms part of the stress response; its excessive activity may also catalyze enzymatic browning, potentially affecting the visual and sensory quality of the product. So, it could be minimized by optimizing ozone dose and exposure time, controlling temperature, and using antioxidants like ascorbic acid, rapid post-treatment

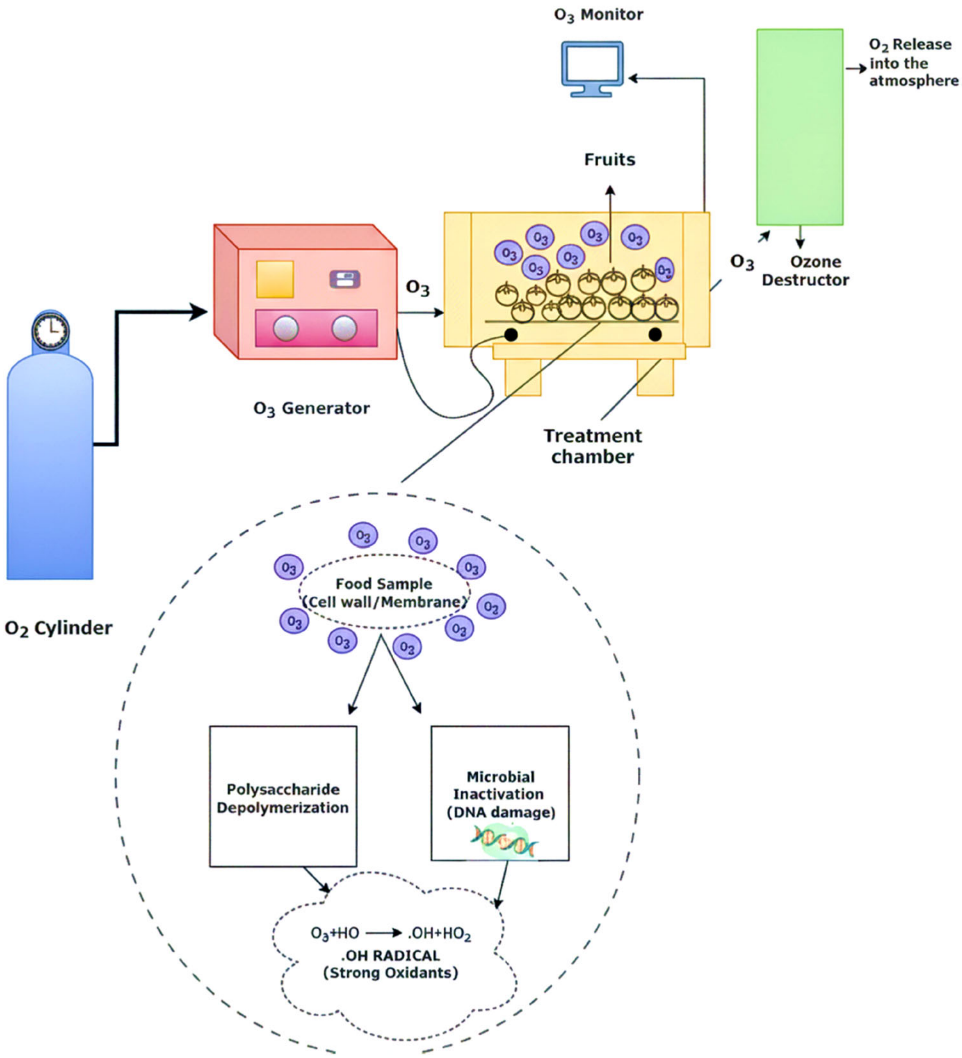

FIGURE 2 | Experimental setup and mechanism involved in the ozone pretreatment of fruit samples.

cooling and proper handling also help preserve color and sensory quality. However, excessive exposure can damage cells and affect volatiles and membranes, highlighting the need for controlled application to preserve quality (Quintero et al. 2021). Ozone pre-treatment enhances polyphenol levels by activating ROS-mediated pathways and stimulating enzymes such as phenylalanine ammonia-lyase (PAL), which promotes phenolic biosynthesis. This effect is particularly evident in post-harvest fruits and vegetables such as strawberries, grapes, berries, lettuce, spinach, and red-veined sorrel. For example, strawberries treated with 5 ppm ozone for 30 min showed an 18.7% increase in total phenolics, 22.4% increase in flavonoids, and 16.3% increase in anthocyanins, linked to enhanced PAL activity (Y. Wang et al. 2019). Similarly, ozone exposure in satsuma mandarin fruits (2–4 mg/L, 60 min) increased total flavonoids by 19.6% and antioxidant capacity by 25%, again associated with elevated PAL activity (Zhu et al. 2019). In blueberries, 2.5 ppm ozone treatment for 3 h raised total phenols by 12.8% and anthocyanins by 14.5%, with PAL activity increasing by 30% (Ye et al. 2020).

Studies on leafy plants such as red-veined sorrel and barley have also confirmed these trends. Ozone gas exposure at 1 ppm enhanced polyphenol accumulation in red-veined sorrel by stimulating phenylpropanoid metabolism (Matłok et al. 2020), while young barley plants exposed to 50 ppb ozone for 14 days showed a 45% increase in PAL activity and 28% higher phenolic content (Serapiglia et al. 2022). Moreover, ozone water washing (4 mg/L, 15 min) of Honeoye strawberries elevated total phenolics by 21.3% and antioxidant activity by 17.2%. These findings confirm that ozone acts as an effective non-thermal pretreatment by triggering oxidative signaling cascades that activate the phenylpropanoid pathway, thereby enriching bioactive phenolic compounds. However, the effects remain dose- and exposure-dependent, requiring controlled application to prevent oxidative damage and preserve sensory quality. Controlled environments like chambers or greenhouses ensure consistent results, as polyphenol production depends on ozone concentration and exposure time. Ozone serves as an effective non-thermal enhancement method (Shafiee and Samani 2024).

ii) **Antioxidants**

Ozone treatment (1 ppm) significantly increased antioxidant levels in marjoram plants, as measured by ABTS (2,2-azinobis diammonium salt, 3-ethylbenzothiazoline-6-sulfonic acid) and DPPH (diphenyl-1-picrylhydrazyl) tests. Antioxidants increased notably after 1 day of ozone exposure, especially with the 3-min treatment. Longer exposures (> 5 days) with 7–10 min durations further enhanced levels by stimulating antioxidative enzymes via calcium channel interactions (Piechowiak et al. 2022). Plants react differently to ozone treatment depending on the species and treatment conditions. For instance, red-veined sorrel plants showed a clear increase in antioxidants, especially after 10 min of ozone treatment on the first day (Matłok et al. 2020). In addition, Ozone treatment of Kalanchoe daigremontianin plants at 10 ppm for 1 min significantly increased antioxidant activity levels: ABTS assay rose 54% and DPPH assay rose 65%, compared to untreated controls (Matłok et al. 2022). The antioxidants significantly increased because ozone triggered an oxidative burst in apoplast plant cells, causing them to produce more small antioxidants that fight harmful molecules. Other studies also found that gaseous ozone boosts antioxidants in plants (Glowacz and Rees 2016).

iii) **Vitamins**

Ozone treatment can impact the plant tissue's ability to regenerate vitamin C, with non-green tissues generally containing lower levels than green tissues. Low ozone concentrations (5 ppm) may reduce ascorbic acid content in leaves due to the activation of ascorbate oxidase, which degrades vitamin C. The oxidation effects vary depending on ozone concentration and exposure duration (Maherani et al. 2019). Ascorbic acid breaks down through oxidation or non-oxidation processes. Ozone molecules or free radicals cause oxidation, converting ascorbic acid into dehydroascorbic acid, which still functions as a vitamin. It can revert to ascorbic acid or degrade into diketogulonic acid, losing its vitamin activity (Shah, Sulaiman, et al. 2019). During stress, ascorbate oxidase activity rises, causing ascorbic acid loss. Research indicates ozone-generated radicals and elevated ascorbate oxidase promote vitamin C degradation. Ozone exposure thus destabilizes vitamin C via oxidative degradation. Controlled ozone can enhance certain antioxidants, but excessive treatment triggers enzymatic and non-enzymatic breakdown of vitamin C (Sachadyn-Krol et al. 2020). Hence, in ozone treatments, controlled exposure is important to enhance extraction or microbial inactivation while minimizing vitamin C loss. Ozone exposure over 50 min reduces ascorbic acid content by approximately 30%–34% in both filtered and unfiltered pummelo juice samples (Shah, Supian, and Hussein 2019) and watermelon juice samples (Lee et al. 2022).

3.2 | Ozone Pretreatment Applications in Fruits, Vegetables, Grains, and Other Agro-Food By-Products

Fruits and vegetables are nutrient-rich but highly perishable, posing risks of spoilage and food-borne illness. Effective cleaning and decontamination are essential, with traditional methods like mild heat treatments commonly used to ensure safety and extend shelf life (Nicola et al. 2022). Heat processing can alter fresh produce's texture, taste, and nutrition, making it unsuitable for some foods. Due to these limitations and rising demand for fresh products, alternative methods like antimicrobial solutions are used, with chlorine and its compounds being common decontaminants in the food industry (Simpson et al. 2022). Chlorine use is banned in some European countries due to harmful by-products and limited effectiveness against pathogens. Recent research focuses on safer, more effective methods to preserve fresh produce quality and safety. The industry seeks methods that inhibit enzymes, eliminate pathogens, and remove pests and residues to extend shelf life. Ozone treatment is a promising solution for fruits and vegetables (Parray et al. 2025). Ozone can be applied in gaseous or aqueous forms: gas is more stable and can be continuously or periodically introduced, while aqueous ozone dissolves in water for washing and sanitizing.

In water, ozone quickly turns into oxygen, with a solubility of 580 mg/L at 27°C. However, its solubility depends on pressure, temperature, pH, bubble size, ozone flow rate, contact time, water purity, and the gas–liquid mixing technology (Seridou and Kalogerakis 2021). Besides, ozone is less stable at high temperatures and pH, decomposes faster in impure water, and dissolves better with smaller bubbles due to increased surface area and reduced mineral interference. (Xiao et al. 2022). Ozone is a safe, eco-friendly option used in various food processing stages, including pre-harvest applications. A study by Tahamolkonan et al. (2022) found that using ozone water through drip irrigation helped improve tomato production. In the food industry, it helps extend the shelf life of fruits and vegetables like apples, carrots, and salads. Ozone water reduces flume water changes, lowering maintenance and wastewater costs. Gaseous ozone also prevents fungal infections in onions and potatoes (Pandiselvam et al. 2019). Farmers who started using this system could grow more marketable produce and recover their equipment costs within the first growing season.

Zhou et al. (2018) demonstrated that gaseous ozone effectively reduced pathogens on fresh and frozen strawberries without affecting quality, highlighting its potential as a sustainable decontamination method requiring pilot-scale optimization. Similarly, Piechowiak et al. (2019) observed that exposing blueberries to ozone (4 ppm at 4°C or 2.5 ppm at 12°C) for 10 days did not effectively control molds and yeasts. However, these ozone treatments did not cause any visible damage to the fruit. Instead, they helped maintain firmness and reduce weight loss, particularly when stored at 12°C. Like chlorine dioxide (ClO_2), ozone can slow down enzymatic activity, which plays a role in preserving firmness and preventing weight loss in certain fruit varieties (C. Li et al. 2022).

Meanwhile, Jaramillo et al. (2019) proposed using aqueous ozone at a concentration of 18 ppm for 10 min to reduce fungal spoilage in blueberries during cold storage without affecting their weight. Ozone plays a crucial role in reducing harmful microorganisms, which are common causes of spoilage and contamination in food products. Ozone disrupts microbial cell structures including cell walls and membranes, which leads to the inactivation or death of bacteria, molds, and yeasts due to its strong oxidative properties. This makes ozone an effective antimicrobial agent in postharvest treatments. Studies have examined the ability of ozone to eliminate harmful microorganisms in blueberries. For instance, Pérez-Lavalle et al. (2020) found that washing blueberries with ozonated water (1.5 mg/L for 5 min) reduced *Escherichia coli* O157:H7 by 3.5 log CFU/g, showcasing ozone's ability to effectively reduce pathogenic bacteria. Concha-Meyer et al. (2015) observed a 3-log reduction in

Listeria monocytogenes after storing blueberries for 10 days in an ozone-rich environment (4 ppm) at 4°C. Meanwhile, Bridges et al. (2018) discovered that closed-circulated gaseous chlorine dioxide ($gClO_2$) was more effective in reducing pathogens than gaseous ozone. These findings indicate that ozone requires higher concentrations and longer exposure periods for significant microbial reduction. Yaseen (2019) observed the *Escherichia coli* reduction in apples by aqueous phase ozone treatment (23–30 mg/L, 3 min), around 3.7 log reduction on the surface, and 1 log reduction in the stem-calyx of the fruit. Dawley et al. (2021) found that ozone was more effective than chlorine in reducing *Bacillus subtilis* spores on lettuce, achieving a 1.56 log reduction, compared to chlorine's 1.30 log reduction. They also observed that wastewater quality improved in chemical and microbial aspects after 10–40 min of ozone treatment, compared to chlorine.

Ozone applied for 0.5–4 min at 0.01–0.07 mg/mL halves the spore germination of *Venturia inaequalis*, *Botrytis cinerea*, and *Neofabraea alba*. Its intense oxidative action disrupts fungal cell membranes by oxidizing lipids, proteins, and enzymes, causing leakage, structural damage, and cell death. Ozone also induces oxidative stress, generating ROS that further damage essential cellular components (Epelle, Macfarlane, et al. 2023). Moreover, Munhos et al. (2019) reported that ozone treatment (28 mg/L for 5 min) reduced *Pseudomonas aeruginosa* by 1 log in skimmed and whole milk. Ozone kills bacteria by oxidizing membrane lipids and proteins, causing structural damage and cell content leakage. The generated ROSs damage enzymes, DNA, and RNA, hindering bacterial survival and reproduction. Its high oxidation potential makes ozone highly effective against *Pseudomonas aeruginosa*, even in milk, positioning it as a potential alternative to pasteurization. Cantalejo et al. (2016) demonstrated that combining ozone treatment (0.6 ppm) with freeze-drying significantly extended the shelf life of chicken fillets by up to 8 months, compared to freeze-drying alone. Ozone treatment reduces aerobic mesophilic and lactic acid bacteria by oxidizing cell walls, membranes, and internal structures, leading to microbial inactivation. When combined with freeze-drying, it removes water, terminating bacterial reproduction. Ozone also limits oxidative rancidity, enhancing chicken fillets' flavor, color, and texture, effectively extending shelf life up to 8 months while maintaining quality.

Ribeiro et al. (2022) studied ozone's ability to control fungal growth (*Fusarium verticillioides, Penicillium* spp., and *Aspergillus flavus*) in maize and its role in detoxifying harmful fumonisins. Their research showed that ozone treatment (13.5 mg/L for 24 h) was a potent antifungal agent, reducing fumonisin B_2 levels by up to 86%. Broberg et al. (2015) studied ozone treatment that affects wheat grain quality by reducing 1000-grain weight, volume weight, and starch concentration, lowering the yield and energy value. However, it increases nutrient concentration and improves baking properties by enhancing protein content and structure, resulting in better dough elasticity, texture, and reduced cadmium levels for enhanced food safety. Hence, these studies highlight ozone's dual role in improving microbial safety while preserving product quality, making it a valuable tool for both extending shelf life and enhancing food safety.

3.3 | Case Studies on Ozone-Assisted Bioactive Compound Recovery

Aslam et al. (2020) stated that using ozone for a long time to clean food might reduce its nutrients. However, it is important to balance food safety and nutrition. Shynkaryk et al. (2015) found that ozone only affects the food surface and does not penetrate deeply, which can be problematic for foods with contamination beyond the surface. However, Karaca and Velioglu (2020) reported that using ozone (950 ± 12 µL/L for 20 min) caused a 40% loss of vitamin C in parsley, indicating a need for careful optimization of ozone treatments to avoid nutrient degradation. Despite this, there is little evidence that ozone affects the protein content or food quality. Üner and Koyuncu (2021) found that treating carrots with ozone (0–5 mg/L gas and 0–10 mg/L water) did not change their weight, firmness, pH, or color, and helped them last longer. However, ozone exposure affected the color of chicken and duck meat by reducing redness due to oxidation of myoglobin and oxymyoglobin.

Chen et al. (2019) investigated the impact of different ozone concentrations (0, 1, 3, and 5 ppm) on postharvest strawberries. During storage, ozone treatment at 5 ppm increased total phenols, flavonoids, and anthocyanins in strawberries. While ozone affects food texture and appearance, it helps maintain color, smell, and texture in various food products, enhancing bioactive compound levels. Lee et al. (2022) investigated the impact of ozone treatment on the quality and microbial inactivation of unclarified and clarified watermelon juice. Ozone treatment for up to 25 min effectively inactivated microbes in unclarified (3.150 log) and clarified (3.466 log) watermelon juice. While °Brix and PME activity remained stable, other properties and bioactive compounds decreased, highlighting ozone's potential as a non-thermal preservation method.

X. Li et al. (2022) studied the effects of fresh-cut red pitaya after ozone treatment, where ozone gas at 2, 4, and 6 mg/L was applied. Ozone treatment (4 mg/L) on fresh-cut red pitaya increased total phenol content, slowed ascorbic acid decline, and enhanced antioxidant capacity by boosting superoxide dismutase (SOD) activity and reducing PPO activity. These findings suggest that optimized ozone treatment can improve agro-products' bioactive compounds and antioxidant properties. However, careful optimization of treatment parameters is necessary to enhance benefits without compromising overall food quality. Despite promising case studies, the implementation of ozone-assisted bioactive recovery at an industrial scale faces several barriers. Nutrient degradation, limited penetration into solid foods, and undesirable sensory changes such as color or texture remain critical challenges. To address and overcome these, optimizing ozone concentration, exposure duration, and delivery methods (gas or aqueous) is essential, as food products respond differently to treatment. Developing standardized protocols supported by real-time monitoring technologies, as demonstrated by Chen et al. (2019) and Lee et al. (2022), can help balance microbial inactivation, nutrient retention, and sensory quality. Nutrient losses, such as the 40% vitamin C reduction in parsley (Karaca and Velioglu 2020), may be mitigated by combining ozone with complementary preservation strategies like modified atmosphere packaging, vacuum sealing, or antioxidant-rich coatings. Since ozone primarily acts on food surfaces (Shynkaryk et al. 2015), using enclosed ozone chambers or integrating with other green technologies, such as ultrasound, mild thermal treatments, or UV-C light, could improve penetration and extraction efficiency. Sensory attributes, such as color and texture, can also be altered, particularly in meat products (Üner and Koyuncu 2021), but using ozone alongside packaging methods that reduce oxidation (such as vacuum sealing) can help to mitigate these effects. Moreover, while ozone is effective in microbial inactivation, it may reduce some bioactive compounds as seen with strawberries (Chen et al. 2019). The use of complementary techniques like antioxidant-rich coatings could enhance post-treatment nutritional benefits. Finally, challenges related to consumer perception and regulatory standards can be addressed through public education campaigns that highlight the safety and benefits of ozone treatments as well as through collaboration with regulatory bodies to establish clear, standardized guidelines that encourage broader acceptance. Overall, a holistic approach that combines optimized ozone protocols with complementary technologies, protective preservation methods, and effective consumer communication can overcome current limitations and unlock the full potential of ozone in sustainable food processing.

4 | Ozone in the Direct Extraction of Bioactive Compounds

OAE influences the strong oxidative potential of ozone to disrupt lignocellulosic structures, promotes mass transfer, cell wall rupture, and enhances the release of bioactive compounds such as phenolics and flavonoids. But if used excessively, its high reactivity can also break down delicate phytochemicals like ascorbic acid, carotenoids, and anthocyanins. The inherent oxidative nature of ozone poses a significant risk of over-oxidation, while this contributes to higher extraction yields and improved selectivity, compared to conventional methods. Sensitive bioactives can undergo structural degradation, leading to reduced bioactivity, altered chemical profiles, and diminished nutritional or therapeutic value (Kaur et al. 2022; Shafiee and Samani 2024). This vulnerability necessitates careful consideration of ozone exposure parameters to prevent loss of compound integrity. Consequently, optimization depends on the matrix. Effective application of OAE requires matrix-specific optimization strategies that account for the unique physicochemical characteristics of each plant material. The variables such as ozone concentration, exposure time, temperature, pH, and solvent system must be finely tuned to maximize extraction efficiency while minimizing oxidative damage. According to Lee et al. (2022), ozone pretreatment at 2 mg/L for 10 min increased polyphenol extraction from grape pomace by 25% without causing a noticeable loss of antioxidants; however, higher levels (>5 mg/L) caused phenolics to degrade oxidatively. Like this, Çelebi et al. (2024) showed that, while retaining color and flavor, ozonated water treatment at 1.5 mg/L for 15 min enhanced the release of flavonoids from citrus peel residues. In contrast, anthocyanin stability decreased with overexposure (>3 mg/L or treatment for more than 20 min). Pérez-Lavalle et al. (2020) demonstrated the effectiveness of ozone in microbial management without compromising sensory quality when they showed that washing blueberries with 1.5 mg/L ozonated water for 5 min decreased *Escherichia coli* O157:H7 by 3.5 log CFU/g. Travaini et al. (2016) optimized ozone pretreatment for lignocellulosic biomass at 0.8 weight percent O_3 per dry biomass to remove lignin selectively, increasing enzymatic hydrolysis yields by 35% while preserving the integrity of the carbohydrates. Together, these results demonstrate that ozone concentrations of 1–3 mg/L in aqueous systems and up to 5 ppm in gaseous form typically yield the best extraction or decontamination results with the least amount of component destruction. For instance, lignin-rich or highly fibrous matrices may tolerate longer ozone exposure for effective cell wall disruption, whereas matrices rich in oxidation-sensitive compounds demand milder conditions to preserve bioactive stability. The choice of solvent can also influence ozone reactivity, with aqueous ethanol mixtures often providing a protective environment, compared to pure aqueous systems (Gullón et al. 2020; Kaur et al. 2022). The balance of enhanced extraction yields with the preservation of compound stability remains dominant. The lack of comprehensive dose-response data specifically correlating ozone parameters with bioactive retention underscores a critical research gap (Gullón et al. 2020; Shafiee and Samani 2024). Therefore, developing real-time monitoring techniques and integrating complementary pretreatments (e.g., enzymatic hydrolysis or ultrasound) could enhance control over oxidative stress during OAE. Hence, to achieve higher yields without sacrificing bioactive stability or sensory qualities, process optimization must carefully balance the ozone dose, exposure time, and product type. In conclusion, while OAE stands out as a sustainable and efficient green extraction technology its successful implementation depends on optimizing process parameters, and matrix-tailored approach that carefully balances yield improvements against the risk of over-oxidation by safeguarding the functional quality of bioactive compounds for food and nutraceutical applications.

4.1 | Role of Ozone in Selective Oxidation to Release Phenolics, Flavonoids, and Carotenoids

Ozone efficiently oxidizes complex biopolymers, especially lignin in plant cell walls, disrupting the structure and enhancing the extraction of intracellular bioactive compounds like phenolics and flavonoids. Lignin, a major structural component, limits access to intracellular bioactives; ozonation breaks aromatic rings and lignin-carbohydrate complexes, improving bioavailability of valuable compounds (Travaini et al. 2016). Ozone cleaves aromatic rings in lignin, producing low-molecular-weight fragments that reduce plant material recalcitrance and enhance bioactive release. This selective oxidation aids phenolic compound extraction, often bound to lignin and hemicellulose. This mechanism has been successfully applied to various substrates, including orange peels (Bechlin et al. 2020), wheat bran (Sonkar et al. 2021), and black elder flowers (Matłok et al. 2020), yielding enhanced concentrations of polyphenols and flavonoids. Bechlin et al. (2020) found that ozone treatment increased phenolic yield in orange peels while preserving antioxidant activity. Lignin oxidation released free phenolics, enhancing the concentration of bioavailable antioxidant compounds. Similarly, Matłok et al. (2020) found that ozone treatment of elderflower extracts resulted in a significant increase in flavonoid content, attributed to the breakdown of cell wall components that previously restricted their solubility and diffusion.

Ozone-induced oxidation rapidly releases lipophilic antioxidant carotenoids from plant tissues by cleaving structural protein and lipid matrices that often bind these pigments, thereby significantly enhancing their solubility, extractability, and overall extraction efficiency beyond lignin disruption (Garcia et al. 2025). Studies on annatto dye waste have demonstrated that OAE effectively degrades undesirable pigments while improving the stability of bioavailable carotenoids (Garcia et al. 2025). Its dual action improves plant-based colorants by degrading off-colors while preserving functional bioactives like carotenoids. Garcia et al. (2025) demonstrated selective removal of unstable pigments without harming bixin and norbixin. Optimal ozone exposure calibration is crucial, as excessive oxidation may induce carotenoid isomerization or cleavage, compromising stability. Similar results have been observed in microalgae, where ozone treatment aids in the recovery of lipophilic bioactives such as phycocyanin, a potent antioxidant pigment derived from Spirulina (Athiyappan et al. 2024; González-Balderas et al. 2020). These findings are significant given that ozone treatment offers a milder alternative to harsh solvents and mechanical disruption for phycocyanin extraction, enhancing cell wall permeability and releasing pigments without considerable degradation. This review focuses on phenolics, flavonoids, and carotenoids due to their high abundance in plant matrices, potent antioxidant and health-promoting properties, significant commercial relevance, and susceptibility to ozone's oxidative action. Ozone treatment can enhance their extractability, stability, and bioavailability, making them particularly suitable for mechanistic studies. These compounds are also the most extensively studied under ozone treatment, providing sufficient data for critical analysis.

4.1.1 | Phenolics

Phenolic compounds are the primary class of antioxidants found in plant materials and exhibit various biological activities such as antimicrobial, antioxidant, and anti-inflammatory properties. The highly reactive and intensive oxidizing capability of ozone can be used for the oxidation of phenols in agro-food components, which can decompose phenolic compounds and their aromatic breakdown products, resulting in substantial decreases in chemical oxygen demand (COD) and organic carbon levels. Two theories explained the interaction of ozone with phenolic compounds: (1) oxidation stress theories, which explain that the ozone molecules facilitate the partial degradation of phenolic cell structure. The second theory explains that the variations or modifications in phenolic compounds are due to the modifications in enzymes triggered by the ozone (Kaur et al. 2022). The ozonation method can attain practically total elimination of phenols, with studies indicating that 4 to 6 moles of ozone are necessary for each mole of phenol (Saputera et al. 2022).

4.1.2 | Flavonoids

Flavonoids are a class of polyphenolic secondary metabolites being synthesized by plants responsible for flavor, color, and pharmacological activities. They also provide resilience against biotic and abiotic challenges. Oxidation of flavonoids can be promoted by the ozone interaction with free radicals, which can improve the bioavailability of flavonoids by the synthesis of phenolic carboxylic acid esters as a substrate in the anaerobic fermentation (Machado et al. 2017). Additionally, ozone interaction with flavonoids can generate novel flavonoids by diminishing the concentration of pre-existing phenolic compounds. Dean (2020) demonstrated that for peanut skins, the total flavonoid content increased as a result of the formation of new flavonoids after ozone treatment, which is believed to liberate flavonoids from their glycosidic components (Dean 2020).

4.1.3 | Carotenoids

Carotenoids are over 750 naturally occurring pigments produced by algae, plants, microorganisms, and through photosynthesis. The oxidation of carotenoids by ozone is mainly due to the Criegee mechanism, which allows the cleavage of alkene double bonds by reaction with ozone, meaning breakage of double bonds (C═C) in carotenoid structures (Garcia et al. 2025). This reaction produces small molecular fragments that consist of functional groups like aldehydes, ketones, and carboxylic acids. These fragments arise from the oxidative cleavage of larger biomolecules like carotenoids, polysaccharides, and lipids during ozone treatment. Ozone is a potent oxidizing agent that targets double bonds and electron-rich sites within these complex molecules, breaking them down into smaller compounds. Bambalele et al. (2023) demonstrated this effect in mango fruit, where ozone exposure led to the degradation of carotenoids into aldehydes and ketones. These smaller molecules play a significant role in altering the fruit's physicochemical properties, including color, aroma, and flavor, which ultimately impact its shelf life and overall quality. The mechanistic pathway behind these changes involves ozone reacting with the conjugated double bonds in carotenoids, leading to cleavage and formation of volatile aldehydes and ketones. These reaction products not only serve as markers of oxidative stress but also influence the sensory characteristics of treated fruits. In parallel, Lee et al. (2022) studied ozone treatment in watermelon juice, where oxidative cleavage affected the polysaccharides such as pectin. The ozone exposure enhanced pectin methylesterase activity, which catalyzes the demethylation and subsequent breakdown of pectin molecules. This process generates smaller fragments containing carboxylic acid groups, affecting the juice's acidity, texture, and microbial stability. The formation of aldehydes and ketones during ozonation is especially important for sensory outcomes. These compounds are often volatile and contribute to the aroma and flavor profile of the food product. Controlled ozone treatment, as shown by Bambalele et al. (2023), can help maintain desirable fresh and fruity notes in mangoes by balancing the degree of oxidative fragmentation. However, excessive production of these molecules may lead to off-flavors or rancidity, highlighting the need for optimization of treatment conditions. Additionally, the generation of carboxylic acids from polysaccharide degradation influences both texture and microbial safety. Lee et al. (2022) reported that increased carboxylic acid content in watermelon juice, resulting from pectin breakdown, can modify viscosity and soften the pulp. Moreover, these acids contribute in lowering the pH, creating an unfavorable environment for microbial growth and thereby extending shelf life. This dual effect demonstrates the potential of ozone treatment as a natural preservation method that balances quality retention with food safety. According to Marston et al. (2015), ozone may oxidize pigments like carotenoids in sorghum flour, decolorizing certain dietary components. The results showed that ozonated sorghum flour shows a brighter or whiter appearance than untreated sorghum flour. The parameters, including ozone concentration, exposure time, and the specific compound type with ozone reacting, can affect the oxidation of the above components.

4.2 | Impact of Ozone on Polyphenol Profile and Antioxidant Activity

Growing demand for minimally processed health-focused foods has spurred interest in non-thermal technologies like ozone treatment. Beyond microbial control, ozone enhances polyphenols, which contribute to the antioxidant, anti-inflammatory, and antimicrobial properties of fruits and vegetables, supporting both nutritional quality and shelf-life extension. Polyphenolic compounds are susceptible to environmental stressors. As studied by Kaur et al. (2022), Ozone's interaction with plant tissues is influenced by treatment variables including ozone concentration, exposure duration, commodity matrix, physiological status, and genotype-specific responses. Beyond decontamination, ozone alters polyphenol profiles via two mechanisms: oxidative degradation of phenolics and stress-induced stimulation of polyphenol biosynthesis through defense pathway activation.

Moderate ozone (under 5 ppm, for controlled, short exposures) acts as a stress elicitor, generating ROS that activate antioxidant protection and upregulate phenolic biosynthesis pathways. Numerous studies across diverse commodities repeatedly confirm this mild, stress-induced, significant enhancement of phenolic compound production. Piechowiak et al. (2020) studied the postharvest impact of ozone on raspberry fruits. A 10-ppm ozone-enriched atmosphere increased free and bound phenolics, including ellagic acid and cyanidin-3-O-glucoside, while improving glutathione redox status. Polyphenol content peaked on the fifth day before declining, suggesting short-term oxidative stress promotes secondary metabolite biosynthesis, but prolonged exposure leads to tissue degradation. Moreover, Matłok et al. (2020) found that ozone exposure (5 ppm for 15 min) affected polyphenol concentrations in highbush blueberries (*Vaccinium corymbosum* L.) differently across genotypes. Cultivars like 'Blue crop' and 'Duke' showed increased chlorogenic acid and quercetin levels, while others had negligible or reduced responses. The study highlighted that genetic variability influences polyphenol response and affects broader metabolomic networks, including changes in sugar profiles linked to polyphenol biosynthesis and carbohydrate metabolism.

The oxidative potential of ozone, while capable of enhancing polyphenol synthesis under controlled conditions, also carries the risk of degradation when misapplied. This is particularly evident in cases where high ozone concentrations or prolonged exposure times were employed. Kaur et al. (2022) highlighted that excessive ozone exposure causes browning and breakdown of catechol or galloyl-containing compounds due to oxidation. Studies also showed that OAE enhances polyphenol yield, modifies antioxidant potential, and improves bioavailability by breaking down complex structures. However, excessive ozone exposure reduces antioxidant capacity and degrades phenolics, emphasizing the importance of controlled application and optimized treatment conditions to preserve bioactive compound integrity (Piechowiak et al. 2020). Excessive ozone exposure can degrade bioactive compounds like flavonoids and anthocyanins, leading to reduced efficacy and loss of their antioxidant and functional properties. (Hasanuzzaman et al. 2020; Kaur et al. 2022; Pandiselvam et al. 2020). Studies on medicinal plants have demonstrated that controlled ozonation can preserve or even enhance the functional and sensory attributes of bioactive compounds, making it a viable method for nutraceutical applications (Shafiee and Samani 2024). Additionally, ozone treatment enhances the storage stability of bioactive compounds by reducing enzymatic degradation and modulating oxidative stress, helping preserve the antioxidant activity of phenolic-rich extracts (Marston et al. 2015).

Ozone interaction with agro-food products can alter polyphenol profiles, either enhancing or reducing phenolic content and antioxidant activity. It also stimulates secondary metabolite formation, including volatile organic compounds, through metabolic changes (Singh et al. 2023). Conversely, excessive ozone exposure induces oxidative stress, elevating lipid peroxidation and ROS, thereby damaging cellular functions. Gaseous ozone exhibits superior oxidative efficacy and stability, whereas ozonated water demonstrates diminished reactivity, potentially suppressing phenolic compound accumulation. Beyond polyphenol content, antioxidant activity serves as a critical metric for evaluating the functional impact of ozone treatment. Piechowiak et al. (2020) found that ozone-treated raspberries exhibited elevated antioxidant activity and phenolic content during early storage. Still, prolonged storage reduced antioxidants, highlighting the importance of controlled post-treatment conditions. Kaur et al. (2022) introduced the concept of "functional ozone dosing," which customizes ozone exposure based on crop-specific responses and intended goals such as microbial control, nutrient preservation, or bioactive enrichment. They recommend combining ozone with methods like cold storage, UV-C, or edible coatings to balance phenolic enhancement and degradation. The study by Tanou et al. (2015) supports this approach, having shown that combining ozone with temperature control or antioxidant pre-treatment can preserve phenolic compounds more effectively than ozone treatment alone.

Additionally, antioxidation involves inhibiting the oxidation of lipids, proteins, and DNA. Ozone activates antioxidant defense in plant cells by regulating ROS and stimulating the synthesis of antioxidants and stress-induced secondary metabolites (Hasanuzzaman et al. 2020). The ozone-induced alterations in antioxidant activity follow the stimulation of secondary metabolism and the modification of both enzymatic and non-enzymatic antioxidant systems (Piechowiak et al. 2020). Ozone's impact on antioxidant activity depends on biomass type, ozone form, concentration, and exposure time. In black elder blossoms, ozone enhanced phytochemical extraction, including polyphenols and vitamin C, and improved antioxidant capacity (Matłok et al. 2020). Ozonation affects both the qualitative and quantitative profile of polyphenols, with changes depending on ozone concentration, exposure time, and plant matrix, as shown in Table 3.

TABLE 3 | Changes in polyphenol composition post-ozonation.

Polyphenol type	Effect of ozone	Reference
Phenolic acids	Increased solubility due to partial oxidation of ester bonds	Bechlin et al. (2020)
Flavonoids	Release from glycosidic complexes, enhancing extraction yield	Kaur et al. (2022)
Tannins	Partial oxidation improves bioavailability, but excessive ozone breaks polymeric structure	Piechowiak et al. (2020)
Anthocyanins	Decreased stability due to oxidative degradation	Matłok et al. (2022)

4.3 | Application of OAE in Functional Food and Nutraceutical Industries

4.3.1 | Functional Foods

Functional foods are enhanced with nutrients or bioactive compounds that offer health benefits. OAE is a novel method for isolating functional food components, improving the yield and quality of bioactive chemicals from food matrices. Gaseous ozone alters the chemical composition of bioactives, enhancing extraction by interacting with proteins, oxidizing the polypeptide backbone, breaking peptide bonds, and modifying amino acid side chains. Ozone treatment has been shown to increase bioactive compounds, such as flavonoids and alkaloids, in chickpeas, thereby enhancing their nutritional profile (Nickhil et al. 2022). Konjac Glucomannan (KGM) is regarded as an indigestible dietary fiber, synthesized to low-viscosity oxidized KGM (OKGM) using an ozone MAE (Y. Li et al. 2021). Bechlin et al. (2020) found that orange peels treated with 40 µg/L ozone and dried at 40°C yielded the highest citrus EO at 4.48 ± 0.07 g 100/g, as ozone broke down oil glands. Additionally, D. Zhang et al. (2022) investigated that ozone (O_3) and ozone-ultrasonic (O_3-US) pretreatments enhanced the structural and functional properties of soluble dietary fibers (SDFs) from lemon peel, with improvements of 85.44% and 92.36%, respectively.

4.3.2 | Nutraceuticals

Nutraceuticals, derived from natural sources, include prebiotics, probiotics, dietary fiber, polyunsaturated fatty acids, antioxidants, vitamins, polyphenols, and spices. Extraction plays a crucial role in isolating and concentrating bioactive compounds, enabling the development of health-benefiting products. OAE utilizes ozone's oxidative properties to enhance the extraction process, breaking down cell walls and releasing valuable phytochemicals from food sector by-products. This method improves the quality, safety, and bioactive content of nutraceutical products while also removing undesirable components, making it a novel and efficient technique for extracting bioactive compounds (Shafiee and Samani 2024). OAE improves nutraceutical production by reducing solvent use, shortening extraction times, and protecting thermosensitive compounds, enhancing efficiency (Bhati et al. 2024). Ozone-assisted autohydrolysis (OAAH) with an optimal ozone dosage of 3% produced 8.9% xylo-oligosaccharides (XOS) from wheat bran at 110°C (Sonar et al. 2021). Additionally, ozone-microwave technology is useful as a dual modification method to produce porous starch without the formation of new functional groups (Subroto et al. 2022).

5 | Ozone as a Solvent Activation Agent

5.1 | Mechanism of Ozone-Enhanced Solvent Extraction

Ozone-enhanced solvent extraction uses a combination of oxidative processes and solvent interactions to improve efficiency. Ozone penetrates microbial cell walls, degrades enzymes, and creates oxidative stress, aiding in the extraction of bioactive components, especially in its aqueous form due to vigorous disinfection activity (Figure 3; Ziyaina and Rasco 2021). Ozone, an advanced oxidation process, serves as a pretreatment to efficiently enhance lignocellulosic biomass suitability for downstream biological processes through destructuration, delignification, and structural deconstruction, thereby reducing recalcitrance, improving enzyme accessibility, and facilitating rapid bioconversion (Arenas-Cárdenas et al. 2017). Rosen et al. (2019) demonstrated that a 15-min ozone pretreatment of shredded mixed municipal trimmings resulted in approximately 20% delignification and a four-fold increase in saccharification efficiency. Ozone treatment offers on-site generation, ambient temperature and pressure oxidation, and selective lignin targeting, preserving cellulose in biomass. These benefits make ozone a promising method for enhancing lignocellulosic biomass for further processing (Baêta et al. 2016).

5.2 | Effects on Solvent Polarity, Reactivity, and Extraction Kinetics

5.2.1 | Solvent Polarity

Solvent polarity significantly impacts the extraction efficiency and mechanism of bioactive compounds, like polyphenols, using ozone-enhanced solvents. Ozone interacts with both polar and non-polar solvents through direct oxidation by oxygen atoms and hydroxyl radicals. Non-polar solvents extract fewer phenolics but more antioxidants, while acidic solutions facilitate selective ozonation, and basic solutions promote non-specific hydroxyl radical reactions (Wei et al. 2017). Incorporating a buffer for pH regulation in ozonation enhances selectivity. Ozone preferentially interacts with lignin, with a higher affinity (1300 M^{-1} s^{-1}), compared to carbohydrates like sucrose and ethanol. Ozone exhibits positive solvatochromism, with a red shift correlating to solvent polarity, enhancing bioactive compound extraction. Additives improve ozone mass transfer by reducing interfacial tension and bubble size, optimizing extraction efficiency. Moreover, the incorporation of additives enhances ozone mass transfer by

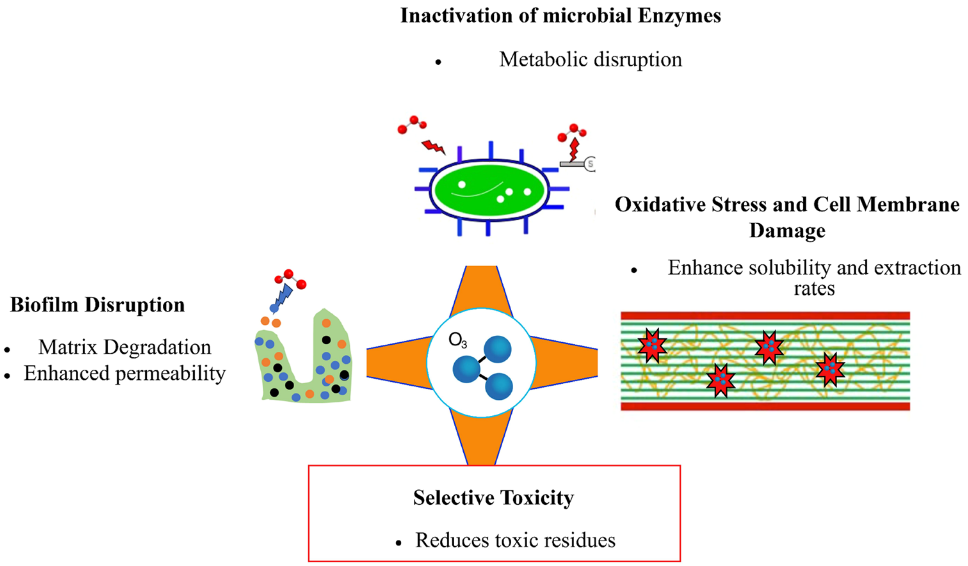

FIGURE 3 | Mechanisms involved in ozone-enhanced solvent extraction.

decreasing the interfacial tension of the liquid phase and reducing bubble size (Tian and Kamran 2023).

5.2.2 | Solvent Reactivity

Solvent reactivity influence's reaction rates and product selectivity in ozone-enhanced solvent extraction. Ozone interacts with biomass to form alcohols and ketones. Aqueous ozone offers better antibacterial efficacy due to enhanced penetration and stability, but its rapid degradation can impact extraction efficiency and target molecule stability, requiring optimized conditions. González-Balderas et al. (2020) demonstrated that ozone pretreatments significantly enhanced the lysis and recovery of biocomponents, reducing solvent usage by 92% and extraction time by 80%–90%. Ozone combined with dilute acid extracted Cu and Zn from rice, yielding 0.20 and 0.08 mg/kg, respectively. This method serves as an effective strategy to enhance the degradation of organic matter comparable to traditional MAE techniques (Pistón et al. 2021). Diffusion enables the transfer of dissolved ozone from water to the substrate surface. However, biomass that is too dry or too wet is ineffective for ozonation. High moisture (> 75%) can block pores, increasing water film thickness, hindering ozone transfer, and leading to nonselective hydroxyl radical formation. Tripathi et al. (2020) found that with pulp moisture between 30% and 50%, the film thickness around fibers approaches zero, allowing easier ozone access. Ozone interaction should occur under acidic conditions to minimize nonselective hydroxyl radical generation. In contrast, when ozone is treated with water under neutral or basic conditions, a higher quantity of hydroxyl radicals is produced, potentially resulting in undesirable side reactions that degrade valuable biomass components (Xiao et al. 2022).

5.2.3 | Extraction Kinetics

Extraction kinetics studies the rate and efficiency of phase changes during extraction. The kinetic model, including short-lived intermediates, accurately estimates ozone concentrations, which increase by at least one order of magnitude without intermediates (Beltrán et al. 2025). The pseudo-first-order kinetic model is a helpful technique for assessing substances more susceptible to ozone deterioration (Derco et al. 2021). The kinetics of solvent extraction focus on how chemical structures and media influence reaction rates. Ozonation and elevated temperatures enhance extraction kinetics, improving phenolic yields. Delignification kinetics were analyzed using first-order and pseudo-first-order models, based on lignin distribution and ozone accessibility in pulp (Dai et al. 2024). Sonkar et al. (2021) investigated the kinetics of ozone delignification for wheat bran, demonstrating that the process adheres to a pseudo-second-order reaction, and the correlation coefficient (r^2) was found to be 0.9977, exceeding the value reported in the pseudo-first-order model.

5.3 | Combination of Ozone With Green Solvents (Water, Ethanol, Supercritical CO_2)

The research efforts have been increasingly focused on replacing traditional solvents with green solvents like water, ethanol, and supercritical carbon dioxide (SC-CO_2) due to their low toxicity, reusability, and efficiency. Combining ozone with green solvents for extracting bioactive compounds from agro-foods offers sustainable, efficient extraction, enhancing compound yield and purity. OAAH was used to produce XOS from wheat bran, with a 3% ozone dosage yielding 8.9% (w/w biomass) at 110°C, outperforming autohydrolysis at 170°C (7.96%; Sonkar et al. 2021). The application of ozone water as an extraction solvent for phycocyanin from spirulina has demonstrated a substantial enhancement in both yield and purity while maintaining its antioxidant capacity (Athiyappan et al. 2024). Similarly, ethanol and ozone together decompose complex structures, reducing polarity and enhancing solubilization. SC-CO_2 with ozone extracts thermolabile compounds without degradation, improving extraction at lower temperatures. SC-CO_2 also destabilizes cellulose and hemicellulose, increasing surface area for enzymatic hydrolysis

(Beluhan et al. 2023). Green solvents enhance the efficiency and selectivity of beneficial substances like antioxidants and colorants, promoting sustainability. However, challenges include optimizing extraction parameters and managing the instability of certain extracts, impacting quality and yield.

5.4 | Comparison With Conventional Solvent-Based Extractions

Ozone is a highly reactive and powerful oxidizing agent widely applied in food processing, pharmaceuticals, and environmental management due to its ability to oxidize a broad range of organic compounds. In the food industry, ozone is used both as a gas in cold storage chambers and as ozonated water for washing and surface decontamination. Treatments typically range from 1 to 5 ppm for fresh produce and juices, effectively inactivating pathogens such as *Escherichia coli, Salmonella*, and *Listeria*, while extending shelf life (X. Li et al. 2022; Kim et al. 2021). In grains, ozone modifies starch and protein structures, improving digestibility and enhancing the release of bioactive compounds. It also facilitates extraction by breaking down lignocellulosic matrices, improving polyphenol yields and antioxidant activity in fruit peels and vegetable residues (Lee et al. 2022; Celebi et al. 2024). Since ozone decomposes into oxygen without leaving residues, it is a safer alternative to chlorine-based disinfectants.

In pharmaceuticals, ozone is widely employed for sterilization and advanced oxidation processes (AOPs). Ozone gas is applied in cleanrooms and production areas to sterilize air and equipment, while ozonated water disinfects contact surfaces and medical tools (Moussavi and Khavanin 2018). In wastewater management, ozone generates hydroxyl radicals and other secondary oxidants that degrade recalcitrant pharmaceutical pollutants, including antibiotics, hormones, and analgesics. Studies report >90% degradation of diclofenac, carbamazepine, and sulfamethoxazole when treated with ozone or ozone-based AOPs (Rosal et al. 2010). This enhances environmental safety by reducing pharmaceutical residues in water bodies. In environmental applications, ozone is used extensively in municipal and industrial wastewater treatment. It oxidizes phenolic compounds, pesticides, and textile dyes into more biodegradable intermediates, thereby improving downstream biological treatment efficiency (Derco et al. 2021). For example, ozone pretreatment has been shown to reduce COD by 40%–60% in pulp and paper effluents and to improve sludge dewaterability (Travaini et al. 2016; Rosen et al. 2021). Its rapid decomposition to oxygen prevents secondary pollution, making it a sustainable and eco-friendly option compared to conventional oxidants.

Table 4a shows the comparison between the ozone and conventional methods of extraction. Environmentally, ozone extraction reduces toxic effluent release and lowers pollution since ozone decomposes into oxygen, unlike traditional organic solvents that contribute to air and water contamination (Derco et al. 2021; Senatore et al. 2019). In terms of efficacy, ozone accelerates extraction by effectively inactivating microorganisms and breaking down complex biomass structures, leading to improved yields of bioactive compounds (Premjit et al. 2022). Ozone pretreatment selectively targets lignin in biomass such as cereal straw, wood pulp, and municipal waste, enhancing enzymatic digestibility and increasing sugar and biofuel yields (Travaini et al. 2016; Rosen et al. 2021). Conventional methods, in contrast, tend to be slower, less efficient, and risk losing sensitive bioactive components due to longer processing times. Moreover, ozone extraction eliminates the need for hazardous solvents offering a low-toxicity alternative that improves safety for operators and consumers (Derco et al. 2021; Gullón et al. 2020). The process also enhances recyclability by generating minimal waste and producing no harmful by-products, unlike conventional solvent disposal methods that often require costly incineration (Garofalo et al. 2022; Vladić et al. 2023). Although ozone extraction entails higher initial investment, it provides long-term cost benefits by reducing environmental management expenses and improving process sustainability (Senatore et al. 2019).

Table 4b shows the comparison of ozone-assisted solvent extraction with conventional methods. This technique reduces solvent volumes by 30%–50% due to increased solubility and mass transfer, making the process greener and more cost-effective (Gil-Martín et al. 2022). It offers higher selectivity, targeting desired bioactive molecules while minimizing co-extraction of impurities, unlike conventional solvent extraction with its broader, less selective profiles (Singh et al. 2023). Processing times are shortened by 40%–60%, improving throughput and reducing energy consumption (Sonkar et al. 2021). Additionally, antioxidant retention is better preserved under OAE, although care must be taken to avoid over-oxidation (Matłok et al. 2020). Overall, ozone-assisted solvent extraction presents a lower environmental impact, decomposing safely into oxygen without leaving harmful residues typical of conventional solvent-based methods (Garofalo et al. 2022). In summary, ozone's strong oxidative properties enable it to serve as a versatile, efficient, and environmentally friendly agent in food, pharmaceutical, and environmental applications. Its use in extraction processes enhances efficiency, selectivity, and safety while significantly reducing solvent use, toxic waste generation, and processing time.

Ozone pretreatment enhances enzymatic digestibility of cellulose and biofuel yields, such as ethanol, by targeting lignin in biomass. Its selective delignification improves biomass destructuration and sugar release during enzymatic hydrolysis. Ozone has been successfully applied to various biomass types, including cereal straw, wood pulp, cotton stalks, grass, and municipal waste, improving their digestibility and biofuel production efficiency (Travaini et al. 2016). Compared to traditional extraction methods, ozone-assisted techniques offer clear advantages in sustainability, cost-effectiveness, and product quality, making them a promising choice for future industrial applications.

6 | Synergistic Approaches: Combining Ozone With Other Extraction Techniques

The continuous expedition to improve the efficiency, yield, and sustainability of extraction processes has led to the exploration of hybrid techniques that combine ozone (O_3) with advanced extraction methods. Ozone is a powerful oxidizing agent that is gaining attention in the food, pharmaceutical, and environmental sectors due to its potential to enhance extraction processes (Botondi et al. 2023). The combination of ozone and other techniques, such as ultrasound, microwave, energy-assisted, and SFE, can

TABLE 4a | Comparison between the Ozone and conventional method of extraction.

Parameters	Ozone	Conventional method
Environmental impact	Reduces chemical oxygen demand (COD) by up to 80% and total organic carbon (TOC) by 60%–75% in industrial effluent (Derco et al. 2021)	Contributes to 20%–30% of industrial VOC emissions; increases COD and TOC in wastewater significantly (Senatore et al. 2019)
Efficacy	Achieves >99.9% microbial inactivation in 5–10 min and also reduces extraction time by 50%–70%; enhances chemical quality (Premjit et al. 2022)	It requires 2–6 h for similar outcomes and often requires higher sample volumes and additional steps to achieve the desired quality.
Extraction Efficiency	Improves sugar yield by up to 65%. Lignin removal increased by 40%–50% through submerged ozonation (Torres-Valenzuela et al. 2020; Rosen et al. 2021).	Conventional approaches demonstrate reduced efficiency and an extended procedure, resulting in the loss of certain sensitive bioactive components.
Toxicity	Generates low toxic residues. Ozone degrades into oxygen naturally; safer for operators (Derco et al. 2021)	It uses solvents like methanol or hexane with high toxicity and volatility. It poses health risks and requires protective handling (Gullón et al. 2020).
Recyclability	Waste reduced by up to 70%; ozone is fully degradable to oxygen and minimal by-product handling needed (Garofalo et al. 2022).	Requires complex waste management and solvent recovery systems where solvent recovery efficiency is often <60% (Vladić et al. 2023)
Cost-effectiveness	Initial equipment cost: $10,000–$30,000 and the operational costs reduced by 30%–40% due to lower energy, chemical, and disposal needs (Rosen et al. 2021).	Lower upfront cost around $2000–$5000, but long-term costs increase by 50%–70% due to solvent purchase, waste treatment, and regulatory compliance (Senatore et al. 2019).
Economic feasibility	ROI achieved in 2–4 years in medium-scale operations; annual operational savings estimated at $5000–$15,000, depending on throughput (industry averages; Derco et al. 2021)	Low initial capex attractive to small operators, but long-term total cost of ownership is higher with hidden costs from environmental compliance and fines possible (Senatore et al. 2019)

bring forth synergistic effects that can maximize the extraction of bioactive compounds (minimizing the usage of solvents and energy; Panigrahi et al. 2023). The recent findings on the synergy between ozone and other extraction techniques exploring their mechanisms, benefits, and potential applications are discussed in this section (Table 5).

6.1 | Ozone-assisted Ultrasound Extraction

Ultrasound-assisted extraction (OAUAE) utilizes high-frequency sound waves to create cavitation bubbles in a liquid medium, leading to the disruption of cell walls and enhancing the release of bioactive compounds. The combination of ozone with ultrasound has shown promising results in improving extraction efficiency. Ozone's oxidative power helps break down the matrix and cell walls more effectively, while ultrasound accelerates the transport of ozone into the matrix, creating a dual mechanism of action (Pistón et al. 2021). A study by Mikucka and Zielińska (2020) demonstrated that OAUAE boosted polyphenol yield from grape pomace by 35% over conventional UAE, with ozone enhancing the release of bioactive compounds from grape skin. The significance of the combined effect of ozone and ultrasound in extracting EOs from herbs was investigated by Floare et al. (2023). The study found a 40% reduction in extraction time and higher EO yield due to ozone's ability to enhance cell membrane permeability. Ozone breaks down lignin and cellulose, while ultrasound's microbubbles improve mass transfer and facilitate ozone penetration into the plant matrix (Pogorzelska-Nowicka et al. 2024).

6.2 | Ozone-Assisted Microwave Extraction

Ozone-assisted microwave extraction (OAMWE) combines ozone and microwave energy to enhance extraction efficiency. The synergy between both techniques accelerates the process by breaking down the sample matrix and increasing the solubility of compounds in the solvent, leading to faster extraction times and improved yield and selectivity. (Huang et al. 2024). The research by Kungsuwan et al. (2023) on the extraction of antioxidant compounds from green tea leaves reported a significant increase in both yield and antioxidant activity. The enhancement of the breakdown of cell walls and the promotion of rapid solvent penetration were achieved by the integration of OAMAE. A study by Bešlo et al. (2022) found that OAMAE improved the extraction efficiency of flavonoids from seeds and peels. The ozone exposure caused oxidative cleavage of flavonoid glycosides, resulting in higher concentrations of free aglycones in the extract. Ozone's

TABLE 4b | Comparison of ozone-assisted solvent extraction with conventional methods.

Parameter	Ozone-assisted solvent extraction	Conventional solvent extraction	Reference
Solvent volume	Reduced by 30%–50% due to enhanced solubility and cell wall disruption	Requires 30%–70% more solvent due to lower mass transfer efficiency	Gil-Martín et al. (2022)
Selectivity	High and selectively targets bioactive molecules like polyphenols and flavonoids	Low and co-extraction of undesirable compounds (e.g., waxes, pigments, fats)	Singh et al. (2023)
Processing time	40%–60% faster due to oxidative reactions enhancing permeability and solubility	Typically takes 2–4x longer, depending on temperature and solvent system	Sonkar et al. (2021)
Antioxidant retention	Improved retention of phenolics and flavonoids (10%–25% higher), though high ozone doses may degrade sensitive compounds	Moderate; thermal degradation may lead to 10%–20% loss of antioxidants during prolonged extraction	Matłok et al. (2022)
Environmental impact	Low and ozone decomposes into oxygen with minimal environmental load	High and generates chemical residues that requires post-treatment, and contributes to VOC emissions	Garofalo et al. (2022)

TABLE 5 | Overview of synergistic approaches: Combining ozone with other extraction techniques.

Sl. no.	Combination technique	Extraction method	Application	Key findings	Advantages	Limitations	References
1.	Ozone + ultrasound	Ultrasound-assisted extraction (UAE)	Essential oils (EOs) from rosemary	Ozone enhances the cavitation effect of ultrasound leading to better oil yield. The combined method reduced extraction time by 40%, compared to traditional methods.	Faster extraction Higher yield Lower solvent usage Eco-friendly	Needs precise control of ozone concentrations as overexposure may lead to degradation of sensitive compounds	de Souza Pedrosa et al. (2021)
2.	Ozone + microwave	Microwave-assisted extraction (MAE)	Polyphenolic compounds from grapes	Ozone synergistically increases the microwave absorption by plant tissues. Resulting in faster polyphenol extraction with higher antioxidant activity	Energy efficiency Increased extraction rate Improved bioactive compound yield	Microwave and ozone interaction can cause undesirable decomposition of some volatile compounds.	Bouchez et al. (2023)
3.	Ozone + steam distillation	Steam distillation	EOs from eucalyptus	The combination of ozone with steam distillation improves the extraction efficiency of EOs. With ozone acting as a facilitator for better mass transfer	Higher quality oils. Reduced usage of solvents. Eco-friendly process	Difficulty in controlling ozone levels and maintaining consistent oil quality	Özüiçli et al. (2023)
4.	Ozone + supercritical CO_2	Supercritical fluid extraction (SFE)	Bioactive compounds from algae	Ozone enhanced the interaction between CO_2 and the biomass. It leads to improved extraction efficiency for high-value compounds like carotenoids and fatty acids.	Higher purity of extracts Reduced solvent usage Eco-friendly process	High operational costs Complexity in controlling the combination of both ozone and supercritical CO_2 conditions	T. Wang et al. (2024)

(Continues)

TABLE 5 | (Continued)

Sl. no.	Combination technique	Extraction method	Application	Key findings	Advantages	Limitations	References
5.	Ozone + enzyme-assisted	Enzyme-assisted extraction (EAE)	Protein extraction from soybeans	The combined ozone-enzyme method significantly improved protein yield. It reduced the need for harsh chemicals. The ozone helps in breaking down cell walls and enhancing enzyme activity.	Milder extraction conditions Higher yield No usage of toxic chemicals	Variability in enzyme efficiency depends on the source Cost of enzymes	Maurya et al. (2020)
6.	Ozone + pressurized liquid extraction (PLE)	PLE	Flavonoids from citrus peel	Ozone helps to break down cellular structure. It allows for better penetration of solvents under higher pressure. It also leads to higher yield and faster extraction times.	Reduced solvent usage Eco-friendly Enhanced extraction of bioactive compounds	Sensitivity of certain compounds to higher pressure and ozone exposure	Perez-Vazquez et al. (2023)
7.	Ozone + subcritical water	Subcritical water extraction (SWE)	Phenolic compounds from grape seeds	Ozone-assisted SWE led to a significant improvement in the extraction of polyphenols. It helped in decreasing the extraction time by 30%, compared to traditional methods.	Higher yield. Faster extraction No organic solvents are needed.	Requires control over temperature and pressure parameters to optimize ozone and water interaction	Afraz et al. (2023)

(Continues)

TABLE 5 | (Continued)

Sl. no.	Combination technique	Extraction method	Application	Key findings	Advantages	Limitations	References
8.	Ozone + solvent extraction	Solvent extraction (SE)	Lipids from microalgae	Combining ozone with solvent extraction resulted in an increased oil yield. It reduced solvent usage with ozone promoting the breakdown of cellular structures to release more lipids.	Higher oil yield Less solvent is required. Improved efficiency	Potential for over-oxidation of lipids. It leads to a decrease in the quality of extracts.	González-Balderas et al. (2020)
9.	Ozone + hydro distillation	Hydro distillation	EOs from mint leaves	Ozone treatment significantly enhanced the hydrodistillation process by increasing the permeability of plant cells. It leads to higher EO yields with better chemical profiles.	Greener methods Increased yield No toxic chemicals	Higher concentrations of ozone can affect the flavor profile of the oil causing undesired effects.	Radivojac et al. (2021)
10.	Ozone + cold pressing	Cold pressing	Citrus juice and oils from oranges	Ozone was used to enhance the cold pressing of citrus fruits by improving the release of EOs and juice. The press resulted in a higher yield and better sensory qualities of the juice.	Non-thermal preserves the natural properties of the product. Higher juice yield	Limited by the need for specialized ozone equipment and the potential degradation of delicate compounds if ozone concentration is not well-controlled.	Park et al. (2024)

oxidative properties disrupt cellular structures, aiding in the release of compounds more easily. Microwave radiation induces the rapid heating of the sample, enhancing the solubility and mass transfer, while ozone enhances the oxidative degradation of complex molecules (Xiao et al. 2022).

6.3 | Ozone Integrated With EAE

EAE utilizes enzymes to selectively break down the cellular components of plant materials, facilitating the release of bioactive compounds. The integration of ozone with enzymes offers a synergistic approach by combining the oxidative power of ozone with the specificity of enzyme catalysis. The combination of the techniques has been explored in the extraction of a wide range of compounds, including EOs, polyphenols, and proteins (Lavenburg et al. 2021). A study by D. Zhang et al. (2022) showed that combining ozone with EAE (OAEAE) improved the extraction of pectin from lemon peel. The ozone treatment weakened the cell walls, allowing enzymes to break down the pectin, leading to higher yields more efficiently. Additionally, in research by C. Zhang et al. (2024), the combination of ozone with cellulase enzymes in the extraction of lignocellulosic biomass resulted in an enhanced yield of fermentable sugars, which could be further utilized in biofuel production. Ozone pretreatment softens the cell walls, making them more susceptible to enzymatic action, leading to improved efficiency in the enzymatic breakdown of complex molecules. The oxidative capacity of ozone also aids in the breakdown of recalcitrant components, which could otherwise hinder the effectiveness of enzymes (Epelle, Yaseen, et al. 2023).

6.4 | SFE With Ozone Integration

Ozone-integrated SFE (OASFE) enhances the oxidative power of CO_2, improving the extraction of heat-sensitive compounds or those with strong molecular bonds, while maintaining the environmental benefits and selectivity of traditional SFEs (Afraz et al. 2023). A study by Aslanbay Guler et al. (2024) investigated the effect of OASFE for the extraction of carotenoids from algae. The research found that ozone improved the extraction efficiency by breaking down the cellular matrix, which allowed CO_2 to penetrate the cells and extract carotenoids more efficiently. Research by Hedayati et al. (2025) on the extraction of EOs from lavender using OASFE CO_2 showed enhanced yields and reduced extraction time, which can be attributed to the synergy between ozone and the supercritical fluid in breaking down cell structures. Ozone aids in breaking the cellular matrix and improving the diffusion of CO_2 into the plant material, leading to more efficient extraction of bioactive compounds. OASFE CO_2 may also modify the solvent properties of CO_2, making it more effective at solubilizing certain compounds (Dhara et al. 2022).

6.5 | Potential for Multi-Stage Hybrid Extraction Systems

Ozone-based hybrid extraction systems demonstrate high efficiency at the laboratory scale, transitioning these innovations to industrial applications presents several technical and regulatory hurdles. It is equally important to assess the scalability and long-term stability of bioactive compounds under such integrated systems, even though the synergistic potential of ozone with ultrasound, microwave, and enzymatic extraction methods presents a promising direction for increasing extraction efficiency, enhanced cell wall disruption, selective compound release, reducing solvent and energy use. Most of the contemporary research is still conducted at the pilot or laboratory levels. The total phenolic yield from grape pomace was shown to increase by 28% using ozone-assisted ultrasound extraction (2 mg/L O_3 with 150 W ultrasound for 15 min) by Lee et al. (2022). However, there is currently no large-scale evidence to support industrial repeatability. Hybrid green extraction systems provide advantages for the environment and efficiency, but before being used in industry, their techno-economic viability needs to be confirmed by thorough cost–benefit and life-cycle analyses. Čechovičienė et al. (2025) reported a 50% increase in antioxidant yield from blackberries using a three-stage extraction approach. Similarly, T. Wang et al. (2024) demonstrated a 35% improvement in polyphenol recovery from microalgae with enhanced antioxidant activity using a combination of ozone pre-treatment, microwave extraction, and supercritical CO_2. Despite these promising outcomes, such systems have largely been validated only in batch-mode operations typically at scales under 10 L, limiting their immediate industrial applicability. Scaling ozone-based systems introduces several mechanical and chemical challenges. One key issue is the oxidative degradation of sensitive bioactive compounds during prolonged or high-dose ozone exposure. Çelebi et al. (2024) stated that exposure above 50 ppm ozone for more than 10 min caused up to 30% degradation of anthocyanins in grape skins. To prevent this, precise control of ozone concentration, exposure time, and ambient conditions is essential. However, achieving this control at large volumes is technically demanding, especially when integrated with high-throughput extraction technologies. Furthermore, continuous exposure to ozone can lead to the corrosion of metallic components, degradation of reactor seals, and shortened equipment lifespans factors that increase maintenance costs and system downtime over time.

Enzyme stability is another challenge when transitioning from lab to industrial scale. In hybrid systems, EAE serves a critical role in selectively targeting and releasing specific compounds. However, repeated use over extended extraction cycles leads to a gradual decline in enzyme activity due to residual ozone exposure and thermal stress. For example, enzyme activity losses of 20%–40% have been observed after five extraction cycles in ozone-integrated systems (Kim et al. 2021). This necessitates frequent replenishment of enzymes, which impacts both process economics and sustainability. Only very few hybrids ozone-based systems have undergone full-scale industrial validation. Fernandes et al. (2024) conducted a techno-economic analysis on an ozone-ultrasound extraction process for fruit waste and found that energy savings of 22% were possible. The overall capital investment was 35% higher, compared to conventional ethanol extraction systems. Furthermore, operational scalability was limited by the availability of modular ozone generation systems capable of stable and continuous output under fluctuating flow conditions, which is a key requirement for industrial extraction lines processing several hundred liters per hour. Regulatory uncertainty for ozone-assisted hybrid system growth remains a major barrier to widespread adoption. In the United States, ozone is classified as GRAS for water and food surface sanitation (21 CFR), but its role as a processing aid in extraction is not explicitly covered by any international standards, leading to ambiguity in its acceptance for extracts used in food or nutraceutical products (Karaca and Velioglu 2020). In Europe, the EFSA continues to assess OAE technologies on a case-by-case basis. The concerns persist regarding potential by-product formation (such as aldehydes or short-chain peroxides), especially if ozone reacts with lipid-rich matrices. The regulatory approval process is slow and inconsistent across jurisdictions without comprehensive toxicological and chemical stability data for each application (Twi-Yeboah et al. 2024; Saravana et al. 2023; Wen et al. 2020).

In conclusion, hybrid ozone-based extraction systems hold great promise for improving bioactive compound recovery in a sustainable and energy-efficient manner. Laboratory studies have demonstrated yield increases of up to 50%, along with reductions in solvent use and processing time. However, the road to industrial implementation is constrained by technical issues such as oxidative degradation, enzyme instability, and equipment wear as well as broader challenges, including insufficient pilot-scale validation and unclear regulatory frameworks. Addressing these limitations will require coordinated efforts in process engineering, regulatory science, and cross-sector collaboration to unlock the full potential of hybrid ozone-based extraction technologies. Future research should thus concentrate on creating industrial-scale trials and putting in place regulatory frameworks that deal with consumer acceptability, chemical stability, and process safety. Such endeavors would close the gap between ozone-assisted hybrid extraction technologies' commercial adoption and laboratory innovation.

7 | Industrial Applications, Challenges, and Regulatory Considerations of Ozone Treatment

7.1 | Industrial Application and Its Challenges

Over the years, growing industrial interest has led several commercial entities to integrate ozone-based technologies for bioactive extraction and biomass valorization (Dubey et al. 2022). In 2021, a European company scaled up ozone treatment to extract flavonoids and antioxidants from citrus peels. This method enhanced the recovery of compounds like hesperidin and naringenin while reducing organic solvent use, promoting sustainability and environmental safety. This study demonstrated both increased bioactive yield and reduced environmental impacts (Rodrigues Machado et al. 2023). A study by Kassem et al. (2022) explored the commercial viability of ozone-based extraction for grape pomace, which is rich in polyphenols and antioxidants. A California winery applied ozone technology to enhance polyphenol and antioxidant extraction for cosmetics, demonstrating improved bioactive yield and cost-effective potential for large-scale industrial applications (Vlotman et al. 2022).

In 2023, a Southeast Asian food company used ozone treatment on vegetable waste to extract bioactive peptides, turning stems and leaves into functional, health-promoting ingredients. (Purkait et al. 2023). Ozone improved peptide release while preserving bioactivity, showcasing commercial potential in sustainable food waste utilization; however, challenges persist in scaling up and ensuring consistent raw material quality (Ronie et al. 2024). Ozone-based extraction is cost-effective, but scalability challenges persist; high initial costs affect SMEs, though energy-efficient, compact generators help reduce investment (Mathur et al. 2022). Fernandes et al. (2024) focused on small-scale ozone applications for food waste valorization, significantly reducing energy and operational costs by optimizing ozone flow rate and concentration.

Scaling ozone-based bioactive extraction processes for large industrial operations has proved challenging due to the variability in food waste composition. A review by Gautam et al. (2024) on the scalability of ozone techniques found that scaling up ozone techniques faces challenges like inconsistent yields and infrastructure modifications in existing facilities. A US case study highlighted the need for robust systems to handle diverse food waste volumes. Despite challenges, the growing demand for natural bioactives in food, cosmetics, and pharma improves economic viability, with scalability dependent on market acceptance. (Martin-Rios et al. 2020). A study by Fraguela-Meissimilly et al. (2023) found that rising demand for antioxidant-rich compounds from food waste, driven by interest in sustainable ingredients. Economic returns rely on consumer acceptance of waste-derived products; scaling ozone-based extraction beyond small-to-medium operations requires improved ozone generation and consistent raw materials for feasibility (Epelle, Yaseen, et al. 2023).

Regulatory frameworks and safety concerns are critical for ozone-based extraction from food waste, with a key challenge being the assurance that no harmful ozone residues remain in the final product (Hamid et al. 2024). The European Food Safety Authority (EFSA) emphasized standardized ozone residue limits in food waste extracts, confirming safe ozone use with proper post-treatment such as filtration or purging for compliance (Lemic et al. 2024). Although ozone is a strong antioxidant, mishandling poses health risks; OSHA guidelines set acceptable workplace concentrations, requiring ozone handling systems to adhere strictly to these safety standards (Hussien et al. 2023). A study by Epelle, Yaseen, et al. 2023 reviewed the importance of proper ventilation, ozone detectors, and PPE in ozone treatment facilities. Failure to implement safety protocols could lead to respiratory issues and eye irritation.

Food-grade products from ozone-treated waste undergo a lengthy, costly regulatory approval process, as the US Food and Drug Administration (FDA) requires comprehensive safety data and documentation on ozone use before permitting their sale (Xue et al. 2023). A study by Tian and Kamran (2023) on regulatory barriers found that regulatory challenges, including allergen testing and contamination control, hinder the widespread adoption of ozone-based bioactive extraction. Optimization of ozone treatment conditions remains a key limitation (Hamid et al. 2024). Heydari et al. (2023) reported that variations in ozone concentration, treatment time, and temperature cause inconsistent yields, highlighting the need for standardized protocols for broader adoption.

Variability in food waste composition that includes moisture, particle size, and contaminants poses a significant challenge for industrial-scale OAE, affecting overall process efficiency (Lisboa et al. 2024). A study by Dos Santos et al. (2024) in Brazil found that raw material variability affected the yield and quality of bioactive compounds extracted from banana peels, highlighting the need for better pre-treatment processes. Ozone generation is energy-intensive, affecting process sustainability; a German study suggested that improved energy management and integration of renewable sources like solar or wind could lower the carbon footprint, enhancing the environmental sustainability of ozone-based extraction (Skoczko 2025).

OAE has proven cost-effective in small-scale applications. However, its long-term economic viability is uncertain due to high initial capital and maintenance costs, especially for small- and medium-sized enterprises (SMEs). Research into cost-reduction strategies, including affordable ozone generation systems, is essential for sustainability. Despite challenges, commercial studies in food, cosmetics, and pharmaceuticals demonstrate ozone's potential as an innovative, sustainable solution for biomass valorization and bioactive extraction (Osorio-Tejada et al. 2024). Although ozone technology is known to reduce long-term operating costs by using less solvent, processing more quickly, and producing less waste, a more balanced assessment of its economic viability must also take into consideration the initial costs of safety infrastructure and regulatory compliance. In comparison to traditional solvent systems, ozone systems can increase capital expenditures by 15%–25% since they need specialized ventilation, ozone destruct units, leak detection sensors, and sealed treatment chambers to assure worker safety. Due to their limited financial and technical resources, small and medium-sized businesses (SMEs) in particular may find it difficult to achieve these safety and environmental compliance requirements. However, advancements in corona discharge generators and low-energy dielectric barrier discharge (DBD) have lowered the ozone production cost to about 0.1–0.2 $/g, resulting in a 20%–30% reduction in overall operating expenses over a 5-year period (Derco et al. 2021). Long-term savings are achieved by eliminating the requirement for post-treatment solvent recovery and disposal systems due to ozone's self-decomposing nature, which is weighed against these expenses. Challenges in process optimization, scalability, regulatory approval, and raw material variability persist; advances in ozone generation, raw material consistency, and safety protocols are crucial for widespread adoption of ozone-based extraction (Lisboa et al. 2024). The ongoing development of more cost-effective and energy-efficient systems, alongside the establishment of regulatory frameworks.

7.2 | Safety Considerations

To mitigate the dangers of food processing and keep the quality of the product, safety measures in the workplace, when processing food using ozone, require strict compliance. It is a strong oxidizer as well as a respiratory irritant and must be dealt with carefully to ensure food and employee safety (Pandiselvam et al. 2019; Xue et al. 2023). Industrial ozone generators utilize automated control systems to ensure ozone concentration levels are maintained, while ambient monitors can determine if surrounding ozone levels are within limits set by the National Institute for Occupational Safety and Health (NIOSH) and OSHA. These levels are monitored using ozone sensors, which make sure the set safe levels of exposure are not exceeded (Pandiselvam et al. 2019).

With the help of ozone destructors, exhaust systems, and sufficient ventilation, leftover ozone is transformed into oxygen, allowing for its safe removal and preventing its accumulation in the processing areas. For their protection, employees working with ozone treatment must do the appropriate PPE, such as gloves, protective eyewear, and either respirators or face masks designed for ozone (Brodowska et al. 2018; Prabha et al. 2015). In high-ozone exposure environments, emergency shutdown procedures and confined space entry protocols should be used in addition to PPE (Pandiselvam et al. 2019; Xue et al. 2023). It is just as important to manage the residual ozone concentration to prevent nutrient loss and sensory changes. Uncontrolled amounts of ozone can be passively converted into oxygen through the use of degassing chambers or by holding the food for a specified time before it gets packaged, all without compromising safety and compliance regulations (Prabha et al. 2015).

7.3 | Environmental Impact

Ozone is a greener alternative to conventional chemical disinfectants and solvents because it naturally breaks down into oxygen without producing harmful by-products. Its use in food processing and wastewater treatment effectively prevents microbial contamination, COD, and biological oxygen demand (BOD), thereby promoting sustainable waste management (Hai et al. 2018). However, excessive ozone emissions into the atmosphere can create ground-level ozone, which is a major cause of smog and a risk to human health and the environment. Appropriate ventilation systems and controlled ozone application are essential to minimizing unintended environmental impact (Xue et al. 2023). Aslanbay Guler et al. (2024) showed a life cycle analysis comparing the environmental impact of sustainable extraction methods, but their study did not address ozone-based processes, which offer benefits like solvent reduction, low energy consumption, and enhanced extraction kinetics.

7.4 | Regulatory Aspects

Guidelines on ozone use in food processing vary by region. In the United States, the FDA has approved ozone for food contact applications, including ingredient processing, microbial inactivation, and surface sanitation (Pandiselvam et al. 2019; Xue et al. 2023). The EFSA evaluated the safety of ozone in food applications and established guidelines for its use in food processing and water treatment (Pandiselvam et al. 2019). Organic certification standards and food safety regulations may prohibit using specific ozone-based treatments in producing organic food (Epelle, Macfarlane, et al. 2023; Prabha et al. 2015). Certifying the safe and effective use of ozone technology in food systems insists on strict agreement with Hazard Analysis and Critical Control Points (HACCP) and Good Manufacturing Practices (GMP; Pandiselvam et al. 2019; Xue et al. 2023).

8 | Future Research Directions

Ozone technology holds great potential in ensuring microbial safety and as an effective sanitizer for equipment across various food industries. It presents a promising alternative to conventional processing methods, enhancing both product safety and quality. The effectiveness of ozone treatment depends on several factors, including water quality, temperature, pH levels, concentration, flow rate, and application mode. Standardizing the ozone treatment process while considering these parameters is essential to address challenges related to inconsistent yields, process optimization, and variability in raw materials. The development of low-cost equipment is crucial for broader adoption, targeting limitations of high initial capital costs, energy-intensive operations, and scalability issues for industrial applications. While ozone technology is evolving, more research is needed to optimize its application, particularly in pre-treatment, which can improve the sensory and texture qualities of plants (Sivaranjani et al. 2021; Shafiee and Samani 2024) and mitigate potential bioactive degradation caused by excessive oxidation or improper process conditions. Ozone enhances textural, color, and aromatic properties, boosting antioxidant enzyme activity and preserving bioactive compounds, providing strategies to maintain product quality and functionality despite oxidative challenges. It effectively retains nutrients and vitamins compared to traditional methods, making ozone a valuable tool for improving postharvest quality and ensuring the safety of medicinal plants (Epelle, Yaseen, et al. 2023). Future research should prioritize the development of low-cost, energy-efficient ozone generation methods to facilitate broader adoption, especially in SMEs. Advances in ozone generator design (such as DBD reactors and corona discharge technologies) show potential for reducing energy consumption while maintaining high ozone output (Derco et al. 2021). The integration of renewable energy sources could further enhance the sustainability of ozone generation systems. In terms of product quality, ozone pretreatment has been shown to positively impact sensory attributes, including texture, color, and aroma by activating antioxidant enzymes and preserving bioactive compounds (Epelle, Yaseen, et al. 2023). Ozone more effectively retains nutrients and vitamins, compared to conventional treatments, contributing to improved postharvest quality of fruits, vegetables, and medicinal plants. However, a critical area for future study is the detailed assessment of sensory effects across diverse food matrices to better understand consumer acceptance and optimize treatment parameters. Future studies should also focus on optimizing hybrid extraction approaches, such as combining ozone with ultrasound, microwave, enzymatic, or supercritical fluid techniques, to further enhance extraction efficiency while minimizing energy and solvent use. Ultrasound can enhance ozone diffusion and penetration into biomass, while EAE complements ozone's lignin degradation by selectively hydrolyzing polysaccharides. MAE adds rapid heating, reducing processing times further. Such hybrid systems represent a promising direction for maximizing efficiency and product quality in the extraction of bioactive compounds. A key limitation of ozone treatment is the potential deterioration of food products caused by overexposure; this can be addressed by combining ozone with hurdle technology, developing optimized protocols for concentration, exposure time, and temperature, thereby extending shelf life and maintaining quality (De et al. 2018). Additionally, consumer awareness of ozone-treated products is lower, compared to other treatments. Public perception often lags behind technological advancements so transparent communication about ozone's safety, environmental benefits, and sensory advantages is essential. Moreover, integrating renewable energy sources like solar or wind for ozone generation could reduce the carbon footprint, improving environmental sustainability. It can be enhanced by developing a safe product at a reasonable cost using ozone technology. Developing cost-effective, safe ozone-treated products with consistent quality will be critical to building market trust (Epelle, Macfarlane, et al. 2023). Overall, ozone technology presents a promising frontier for enhancing food safety and quality sustainably. The continued interdisciplinary research focusing on equipment innovation, process optimization, sensory evaluation, and consumer education will drive its successful industrial application in the coming years.

9 | Conclusion

The application of ozone as a non-thermal pretreatment, direct extraction enhancer, and solvent activation agent presents a revolutionary approach to bioactive compound recovery from agro-food biomass. This review offers an in-depth synthesis of current research on ozone technology, detailing its mechanisms, effectiveness, and practical applications across diverse agro-food matrices. By critically evaluating ozone's role in enhancing bioactive compound extraction, preserving nutritional and sensory quality, and improving microbial safety, the review provides valuable insights and guidance for both researchers and industry practitioners, promoting innovation in sustainable food processing and encouraging eco-friendly extraction strategies. Through cell wall modification, increased membrane permeability, and selective oxidation, ozone significantly enhances the efficiency and sustainability of bioactive extraction. Ozone technology is gaining traction not only for its efficiency and environmental benefits but also for its potential economic advantages. Recent economic analyses suggest that ozone pretreatment can be implemented using relatively low-cost equipment, which contributes to its feasibility for industrial applications. The capital expenditure for ozone generation systems has decreased significantly due to advances in ozone generator technology, making it accessible even for small- to medium-scale operations (Derco et al. 2021). Moreover, ozone's self-decomposing nature reduces operational costs associated with solvent recovery and waste treatment, offering further economic benefits. It has been demonstrated that, despite a higher initial investment, ozone pretreatment results in lower overall costs when considering reduced processing time, enhanced extraction yields, and minimized environmental compliance expenses (Senatore et al. 2019). This makes ozone a competitive option, compared to traditional extraction methods that rely heavily on costly organic solvents and generate hazardous waste. Furthermore, the integration of ozone pretreatment with other emerging extraction technologies such as ultrasound, microwave, and enzyme-assisted methods paves the way for hybrid extraction systems synergistically improve cell wall disruption, increase mass transfer rates, preserving functional properties with higher extraction yields and improved bioactive stability (Gil-Martín et al. 2022; Singh et al. 2023). However, challenges remain in optimizing ozone treatment parameters for different food matrices, ensuring long-term bioactive stability, and addressing safety and regulatory considerations for industrial-scale applications. Optimization of ozone treatment parameters (such as concentration, exposure time, and temperature) is essential for different food matrices to ensure maximal extraction yields without compromising bioactive stability. Overexposure to ozone can lead to excessive oxidation and degradation of sensitive compounds, necessitating precise control and monitoring. Additionally, safety concerns related to ozone's toxicity at high concentrations must be addressed, requiring proper containment and ventilation systems in industrial setups. Future research should focus on optimizing ozone treatment parameters for different commodities, scaling up industrial applications, exploring novel bioactive targets in pharmaceuticals and cosmetics, and evaluating techno-economic and environmental feasibility. By adopting ozone technology, the food industry can move toward a more sustainable and resource-efficient model, reducing agro-industrial waste while enhancing functional ingredient recovery.

Author Contributions

G. Jeevarathinam: methodology, supervision, conceptualization, investigation, writing–original draft, review, and editing. **Abhipriya Patra**: methodology, conceptualization, writing–original draft, review, and editing. **J. Deepa**: writing–original draft, review, and editing. **R. Rahul**: writing–original draft. **C. S. Neethu**: writing–original draft. **Pentala Mallesham**: writing–original draft. **S. Ganga Kishore**: writing–original draft. **Madhuresh Dwivedi**: writing–original draft. **Siva Shankar V**: writing–original draft. **Punit Singh**: writing–original draft. **Sarvesh Rustagi**: writing–original draft. **Syed Mohammed Basheeruddin Asdaq**: writing–original draft.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No datasets were generated or analyzed during the current study.

References

Afraz, M. T., X. Xu, M. Adil, et al. 2023. "Subcritical and Supercritical Fluids to Valorize Industrial Fruit and Vegetable Waste." *Foods* 12: 2417.

Anjali, K., C. Reshma, N. Sruthi, et al. 2024. "Influence of Ozone Treatment on Functional and Rheological Characteristics of Food Products: An Updated Review." *Critical Reviews in Food Science & Nutrition* 64, no. 12: 3687–3701.

Arenas-Cárdenas, P., A. López-López, G. E. Moeller-Chávez, and E. León-Becerril. 2017. "Current Pretreatments of Lignocellulosic Residues in the Production of Bioethanol." *Waste and Biomass Valorization* 8: 161–181.

Aslam, R., M. S. Alam, and P. A. Saeed. 2020. "Sanitization Potential of Ozone and Its Role in Postharvest Quality Management of Fruits and Vegetables." *Food Engineering Reviews* 12: 48–67.

Aslanbay Guler, B., U. Tepe, and E. Imamoglu. 2024. "Sustainable Point of View: Life Cycle Analysis for Green Extraction Technologies." *ChemBioEng Reviews* 11, no. 2: 348–362.

Athiyappan, K. D., W. Routray, and B. Paramasivan. 2024. "Phycocyanin From Spirulina: A Comprehensive Review on Cultivation, Extraction, Purification, and Its Application in Food and Allied Industries." *Food and Humanity* 2: 100235.

Baêta, B. E. L., D. R. S. Lima, O. F. H. Adarme, L. V. A. Gurgel, and S. F. de Aquino. 2016. "Optimization of Sugarcane Bagasse Autohydrolysis for Methane Production From Hemicellulose Hydrolyzates in a Biorefinery Concept." *Bioresource Technology* 200: 137–146.

Bambalele, N. L., A. Mditshwa, L. S. Magwaza, and S. Z. Tesfay. 2023. "Postharvest Effect of Gaseous Ozone on Physicochemical Quality, Carotenoid Content and Shelf-Life of Mango Fruit." *Cogent Food & Agriculture* 9, no. 1: 2247678.

Bechlin, T. R., S. J. Granella, D. Christ, S. R. M. Coelho, and C. H. D. O. Paz. 2020. "Effects of Ozone Application and Hot-Air Drying on Orange Peel: Moisture Diffusion, Oil Yield, and Antioxidant Activity." *Food and Bioproducts Processing* 123: 80–89.

Beltrán, F. J., M. A. Jiménez-López, P. M. Álvarez, and F. J. Rivas. 2025. "Kinetic Modelling of Ozonation and Photolytic Ozonation of Metronidazole Removal From Water." *Journal of Industrial and Engineering Chemistry* 144: 654–662.

Beluhan, S., K. Mihajlovski, B. Šantek, and M. Ivančić Šantek. 2023. "The Production of Bioethanol From Lignocellulosic Biomass: Pretreatment Methods, Fermentation, and Downstream Processing." *Energies* 16, no. 19: 7003.

Bešlo, D., G. Došlić, D. Agić, et al. 2022. "Polyphenols in Ruminant Nutrition and Their Effects on Reproduction." *Antioxidants* 11, no. 5: 970.

Bhati, D., A. Singh, and G. Kaur. 2024. "Ozone Technology in Food Disinfection." In *Emerging Techniques for Food Processing and Preservation*, edited by S. Kapoor, G. Kaur, B. N. Dar, and S. Sharma, 83–120. CRC Press.

Botondi, R., M. Lembo, C. Carboni, and V. Eramo. 2023. "The Use of Ozone Technology: An Eco–Friendly Method for the Sanitization of the Dairy Supply Chain." *Foods* 12, no. 5: 987.

Bouchez, A., P. Vauchel, S. Périno, and K. Dimitrov. 2023. "Multi-Criteria Optimization Including Environmental Impacts of a Microwave-Assisted Extraction of Polyphenols and Comparison With an Ultrasound-Assisted Extraction Process." *Foods* 12, no. 9: 1750.

Bridges, D. F., B. Rane, and V. C. Wu. 2018. "The Effectiveness of Closed-Circulation Gaseous Chlorine Dioxide or Ozone Treatment Against Bacterial Pathogens on Produce." *Food Control* 91: 261–267.

Broberg, M. C., Z. Feng, Y. Xin, and H. Pleijel. 2015. "Ozone Effects on Wheat Grain Quality–A Summary." *Environmental Pollution* 197: 203–213.

Brodowska, A. J., A. Nowak, A. Kondratiuk-Janyska, M. Piątkowski, and K. Śmigielski. 2017. "Modelling the Ozone-Based Treatments for Inactivation of Microorganisms." *International Journal of Environmental Research & Public Health* 14, no. 10: 1196.

Brodowska, A. J., A. Nowak, and K. Śmigielski. 2018. "Ozone in the Food Industry: Principles of Ozone Treatment, Mechanisms of Action, and Applications: An Overview." *Critical Reviews in Food Science & Nutrition* 58, no. 13: 2176–2201.

Brodowska, A. J., K. Śmigielski, A. Nowak, A. Czyżowska, and A. Otlewska. 2015. "The Impact of Ozone Treatment in Dynamic Bed Parameters on Changes in Biologically Active Substances of Juniper Berries." *PLoS ONE* 10, no. 12: e0144855.

Cantalejo, M. J., F. Zouaghi, and I. Pérez-Arnedo. 2016. "Combined Effects of Ozone and Freeze-Drying on the Shelf-Life of Broiler Chicken Meat." *LWT-Food Science and Technology* 68: 400–407.

Čechovičienė, I., Ž. Tarasevičienė, E. Hallman, A. Jabłońska-Trypuć, L. Česonienė, and D. Šileikienė. 2025. "Ultrasound and Microwave-Assisted Extraction of Blackberry (*Rubus fruticosus* L.) Pomace: Analysis of Chemical Properties and Anticancer Activity." *Plants* 14, no. 3: 384.

Çelebi, Y., G. Ç. Koç, Ö. Süfer, et al. 2024. "Impact of Ozone Treatment on Lipid Oxidation in Foods: A Critical Review." *Ozone: Science & Engineering* 46, no. 5: 430–454.

Chen, C., H. Zhang, C. Dong, et al. 2019. "Effect of Ozone Treatment on the Phenylpropanoid Biosynthesis of Postharvest Strawberries." *RSC Advances* 9, no. 44: 25429–25438.

Concha-Meyer, A., J. D. Eifert, R. C. Williams, J. E. Marcy, and G. E. Welbaum. 2015. "Shelf-Life Determination of Fresh Blueberries (*Vaccinium corymbosum*) Stored Under Controlled Atmosphere and Ozone." *International Journal of Food Science* 2015, no. 1: 164143.

Dai, M., Q. Niu, S. Wu, Y. Lin, J. K. Biswas, and C. J. E. C. L. Yang. 2024. "Hydroxyl Radicals in Ozone-Based Advanced Oxidation of Organic Contaminants: A Review." *Environmental Chemistry Letters* 22, no. 6: 3059–3106.

Dawley, C. R., J. A. Lee, and K. E. Gibson. 2021. "Reduction of Norovirus Surrogates Alone and in Association With Bacteria on Leaf Lettuce and Tomatoes During Application of Aqueous Ozone." *Food and Environmental Virology* 13: 390–400.

Dean, L. L. 2020. "Extracts of Peanut Skins as a Source of Bioactive Compounds: Methodology and Applications." *Applied Sciences* 10, no. 23: 8546.

Derco, J., A. Ž. Gotvajn, O. Čižmárová, J. Dudáš, L. Sumegová, and K. Šimovičová. 2021. "Removal of Micropollutants by Ozone-Based Processes." *Processes* 9, no. 6: 1013.

De Souza, L. P., L. R. D. A. Faroni, F. F. Heleno, et al. 2018. "Effects of Ozone Treatment on Postharvest Carrot Quality." *LWT* 90: 53–60.

de Souza Pedrosa, G. T., T. C. Pimentel, M. Gavahian, L. L. de Medeiros, R. Pagán, and M. Magnani. 2021. "The Combined Effect of Essential Oils and Emerging Technologies on Food Safety and Quality." *LWT* 147: 111593.

Dhara, O., K. P. Rani, and P. P. Chakrabarti. 2022. "Supercritical Carbon Dioxide Extraction of Vegetable Oils: Retrospective and Prospects." *European Journal of Lipid Science and Technology* 124, no. 8: 2200006.

Dubey, P., A. Singh, and O. Yousuf. 2022. "Ozonation: an Evolving Disinfectant Technology for the Food Industry." *Food and Bioprocess Technology* 15, no. 9: 2102–2113.

Epelle, E. I., A. Macfarlane, M. Cusack, et al. 2023. "Ozone Application in Different Industries: A Review of Recent Developments." *Chemical Engineering Journal* 454: 140188.

Epelle, E. I., M. Yaseen, A. Macfarlane, M. Cusack, A. Burns, and L. Rolland. 2023. "Automation of Large-Scale Gaseous Ozonation: A Case Study of Textile and PPE Decontamination." *Sustainability* 15, no. 3: 2216.

Fernandes, J., P. J. Ramísio, and H. Puga. 2024. "A Comprehensive Review on Various Phases of Wastewater Technologies: Trends and Future Perspectives." *Eng* 5, no. 4: 2633–2661.

Floare, A. D., R. Dumitrescu, V. T. Alexa, et al. 2023. "Enhancing the Antimicrobial Effect of Ozone With *Mentha piperita* Essential Oil." *Molecules (Basel, Switzerland)* 28, no. 5: 2032.

Fraguela-Meissimilly, H., J. M. Bastías-Monte, C. Vergara, et al. 2023. "New Trends in Supercritical Fluid Technology and Pressurized Liquids for the Extraction and Recovery of Bioactive Compounds From Agro-Industrial and Marine Food Waste." *Molecules (Basel, Switzerland)* 28, no. 11: 4421.

Garcia, P. C., M. N. Esperança, J. R. Turquetti, and A. L. de Castro Peixoto. 2025. "Carotenoid Degradation in Annatto Dye Wastewater Using an O_3/H_2O_2 Advanced Oxidation Process." *Processes* 13, no. 3: 824.

Garofalo, S. F., F. Demichelis, G. Mancini, T. Tommasi, and D. Fino. 2022. "Conventional and Ultrasound-Assisted Extraction of Rice Bran Oil With Isopropanol as Solvent." *Sustainable Chemistry and Pharmacy* 29: 100741.

Gautam, S., A. Gautam, J. Pawaday, R. K. Kanzariya, and Z. Yao. 2024. "Current Status and Challenges in the Commercial Production of Polyhydroxyalkanoate-Based Bioplastic: A Review." *Processes* 12, no. 8: 1720.

Gil-Martín, E., T. Forbes Hernández, M. A. Romero Martínez, D. Cianciosi, F. Giampieri, and M. Battino. 2022. "Influence of the Extraction Method on the Bioactive Phenolic Compounds Recovery From Food Industry By-Products." *Food Chemistry* 378: 131918. https://doi.org/10.1016/j.foodchem.2021.131918.

Glowacz, M., and D. Rees. 2016. "Exposure to Ozone Reduces Postharvest Quality Loss in Red and Green Chilli Peppers." *Food Chemistry* 210: 305–310.

González-Balderas, R. M., S. B. Velásquez-Orta, I. Valdez-Vazquez, and M. O. Ledesma. 2020. "Intensified Recovery of Lipids, Proteins, and Carbohydrates From Wastewater-Grown Microalgae *Desmodesmus* Sp. by Using Ultrasound or Ozone." *Ultrasonics Sonochemistry* 62: 104852.

Gozé, P., L. Rhazi, L. Lakhal, P. Jacolot, A. Pauss, and T. Aussenac. 2017. "Effects of Ozone Treatment on the Molecular Properties of Wheat Grain Proteins." *Journal of Cereal Science* 75: 243–251.

Greene, A. K., Z. B. Güzel-Seydim, and A. C. Seydim. 2012. "Chemical and Physical Properties of Ozone." In *Ozone in Food Processing*, edited by C. P. O'Donnell, 19–31. Wiley.

Gullón, P., B. Gullón, A. Romaní, G. Rocchetti, and J. M. Lorenzo. 2020. "Smart Advanced Solvents for Bioactive Compounds Recovery From Agri-Food By-Products: A Review." *Trends in Food Science & Technology* 101: 182–197.

Gutierrez, D. R., M. L. Lemos, and S. D. C. Rodriguez. 2018. "Effect of UV-C and Ozone on the Bioactive Compounds and Antioxidant Capacity of Minimally Processed Rocket (Eruca Sativa Mill.)." *International Journal of New Technology and Research* 4, no. 9: 23–29.

Hai, F. I., S. Yang, M. B. Asif, et al. 2018. "Carbamazepine as a Possible Anthropogenic Marker in Water: Occurrences, Toxicological Effects, Regulations and Removal by Wastewater Treatment Technologies." *Water* 10, no. 2: 107.

Hamid, Z., B. K. Meyrick, J. Macleod, E. A. Heath, and J. Blaxland. 2024. "The Application of Ozone Within the Food Industry, Mode of Action, Current and Future Applications, and Regulatory Compliance." *Letters in Applied Microbiology* 77, no. 11: ovae101.

Hasanuzzaman, M., M. B. Bhuyan, F. Zulfiqar, et al. 2020. "Reactive Oxygen Species and Antioxidant Defense in Plants Under Abiotic Stress: Revisiting the Crucial Role of a Universal Defense Regulator." *Antioxidants* 9, no. 8: 681.

Hedayati, S., M. Tarahi, A. Madani, S. M. Mazloomi, and M. H. Hashempur. 2025. "Towards a Greener Future: Sustainable Innovations in the Extraction of Lavender (Lavandula spp.) Essential Oil." *Foods* 14, no. 1: 100.

Heydari, M., K. Carbone, F. Gervasi, et al. 2023. "Cold Plasma-Assisted Extraction of Phytochemicals: A Review." *Foods* 12, no. 17: 3181.

Huang, H., Z. Ni, J. Xie, et al. 2024. "Good Feasibility of Ozone-Microwave Treatment as a Sterilization Technology to Extend the Edible Life of Candied Fruit as a Post-Processed Fresh Fruit Product." *Food and Bioprocess Technology* 17, no. 10: 3086–3100.

Hussien, A. A., K. K. Alzboon, W. Matalqa, and A. H. AlEssa. 2023. "Health Risk Assessment Due to Indoor Air Pollution in Air Conditioning Manufacturing Plants." *International Journal of Safety & Security Engineering* 13, no. 6: 1083–1090.

Jafari, S. M., and N. Therdthai. 2022. *Non-Thermal Food Processing Operations: Unit Operations and Processing Equipment in the Food Industry*. Woodhead Publishing.

Jaramillo, S. G., E. V. Contigiani, M. A. Castro, et al. 2019. "Freshness Maintenance of Blueberries (*Vaccinium corymbosum* L.) During Postharvest Using Ozone in Aqueous Phase: Microbiological, Structure, and Mechanical Issues." *Food and Bioprocess Technology* 12: 2136–2147.

Karaca, H., and Y. S. Velioglu. 2020. "Effects of Ozone and Chlorine Washes and Subsequent Cold Storage on Microbiological Quality and Shelf Life of Fresh Parsley Leaves." *LWT* 127: 109421.

Kassem, H. S., M. E. Tarabih, H. Ismail, and E. E. Eleryan. 2022. "Effectiveness of Ozonated Water for Preserving Quality and Extending Storability of Star Ruby Grapefruit." *Processes* 10, no. 2: 277.

Kaur, K., R. Pandiselvam, A. Kothakota, S. P. Ishwarya, R. Zalpouri, and N. K. Mahanti. 2022. "Impact of Ozone Treatment on Food Polyphenols–A Comprehensive Review." *Food Control* 142: 109207.

Kim, J., J. Park, and J. Lee. 2021. "Ozone Treatment for Microbial Inactivation in Fresh Produce: Mechanisms and Applications." *Food Control* 123: 107859. https://doi.org/10.1016/j.foodcont.2020.107859.

Kungsuwan, K., C. Sawangrat, S. Ounjaijean, S. Chaipoot, R. Phongphisutthinant, and P. Wiriyacharee. 2023. "Enhancing Bioactivity and Conjugation in Green Coffee Bean (*Coffea arabica*) Extract Through Cold Plasma Treatment: Insights Into Antioxidant Activity and Phenolic–protein Conjugates." *Molecules (Basel, Switzerland)* 28, no. 20: 7066.

Lavenburg, V. M., K. A. Rosentrater, and S. Jung. 2021. "Extraction Methods of Oils and Phytochemicals From Seeds and Their Environmental and Economic Impacts." *Processes* 9, no. 10: 1839.

Lee, B. J., A. S. Y. Ting, and Y. Y. Thoo. 2022. "Impact of Ozone Treatment on the Physico-Chemical Properties, Bioactive Compounds, Pectin Methylesterase Activity and Microbiological Properties of Watermelon Juice." *Journal of Food Science & Technology* 59, no. 3: 979–989.

Leeuwen, J. V., R. Pandiselvam, and G. Jeevarathinam. 2024. "Cost Estimation for the Preservation of Selected Food/Crop Products With Ozone." *Journal of Food Process Engineering* 47, no. 11: e14772.

Lemic, D., M. A. Galešić, M. Bjeliš, and H. Viric Gasparic. 2024. "Ozone Treatment as a Sustainable Alternative for Suppressing Blue Mold in Mandarins and Extending Shelf Life." *Agriculture* 14, no. 7: 1196.

Li, C., S. Wang, J. Wang, Z. Wu, Y. Xu, and Z. Wu. 2022. "Ozone Treatment Promotes Physicochemical Properties and Antioxidant Capacity of Fresh-Cut Red Pitaya Based on Phenolic Metabolism." *Frontiers in Nutrition* 9: 1016607.

Li, X., Y. Chen, and H. Zhang. 2022. "Effects of Ozone Treatment on Microbial Safety and Quality of Fresh-Cut Red Pitaya." *Postharvest Biology and Technology* 193: 111024. https://doi.org/10.1016/j.postharvbio.2022.111024.

Li, Y., H. Liu, Y. Xie, K. I. Shabani, and X. Liu. 2021. "Preparation, Characterization and Physicochemical Properties of Konjac Glucomannan Depolymerized by Ozone Assisted With Microwave Treatment." *Food Hydrocolloids* 119: 106878.

Lisboa, H. M., M. B. Pasquali, A. I. dos Anjos, et al. 2024. "Innovative and Sustainable Food Preservation Techniques: Enhancing Food Quality, Safety, and Environmental Sustainability." *Sustainability* 16, no. 18: 8223.

Machado, N. F., and R. Domínguez-Perles. 2017. "Addressing Facts and Gaps in the Phenolics Chemistry of Winery By-Products." *Molecules (Basel, Switzerland)* 22, no. 2: 286.

Maherani, B., M. Harich, S. Salmieri, and M. Lacroix. 2019. "Antibacterial Properties of Combined Non-Thermal Treatments Based on Bioactive Edible Coating, Ozonation, and Gamma Irradiation on Ready-to-Eat Frozen Green Peppers: Evaluation of Their Freshness and Sensory Qualities." *European Food Research and Technology* 245: 1095–1111.

Mamleeva, N., S. Autlov, N. Bazarnova, and V. Lunin. 2016. "Degradation of Polysaccharides and Lignin in Wood Ozonation." *Russian Journal of Bioorganic Chemistry* 42: 694–699.

Marston, K., H. Khouryieh, and F. Aramouni. 2015. "Evaluation of Sorghum Flour Functionality and Quality Characteristics of Gluten-Free Bread and Cake as Influenced by Ozone Treatment." *Food Science and Technology International* 21, no. 8: 631–640.

Martin-Rios, C., A. Hofmann, and N. Mackenzie. 2020. "Sustainability-Oriented Innovations in Food Waste Management Technology." *Sustainability* 13, no. 1: 210.

Mathur, S., G. Gosnell, B. K. Sovacool, et al. 2022. "Industrial Decarbonization via Natural Gas: A Critical and Systematic Review of Developments, Socio-Technical Systems and Policy Options." *Energy Research & Social Science* 90: 102638.

Matłok, N., I. Kapusta, T. Piechowiak, M. Zardzewiały, J. Gorzelany, and M. Balawejder. 2020. "Characterisation of some Phytochemicals Extracted From Black Elder (*Sambucus nigra* L.) Flowers Subjected to Ozone Treatment." *Molecules (Basel, Switzerland)* 26, no. 18: 5548.

Matłok, N., T. Piechowiak, I. Kapusta, K. Królikowski, and M. Balawejder. 2022. "Induction of Biosynthesis Antioxidant Molecules in Young Barley Plants by Trioxygen." *Molecules (Basel, Switzerland)* 27, no. 21: 7195.

Maurya, V. K., S. K. Gupta, M. Sharma, et al. 2020. "Growth, Physiological and Proteomic Responses in Field Grown Wheat Varieties Exposed to Elevated CO_2 Under High Ambient Ozone." *Physiology and Molecular Biology of Plants* 26: 1437–1461.

Meher, P., N. Deshmukh, A. Mashalkar, and D. Kumar. 2023. "Ozone (O_3) Generation and Its Applications: A Review." Paper presented at the AIP Conference Proceedings, Dalesice, Czech Republic, August 17–18.

Mikucka, W., and M. Zielińska. 2020. "Distillery Stillage: Characteristics, Treatment, and Valorization." *Applied Biochemistry and Biotechnology* 192: 770–793.

Mottan, S., N. Gupta, M. Sood, J. D. Bandral, and J. S. Anju Bhat. 2022. "A Review on Ozone Technology in Food Industry." *Pharma Innovation Journal* SP-11, no. 6: 759–764.

Moussavi, G., and A. Khavanin. 2018. "Application of Ozone and Ozone-Based Advanced Oxidation Processes in Pharmaceutical Wastewater Treatment." *Journal of Environmental Chemical Engineering* 6, no. 4: 4761–4775. https://doi.org/10.1016/j.jece.2018.07.012.

Munhõs, M. C., R. S. Navarro, S. C. Nunez, D. I. Kozusny-Andreani, and A. Baptista. 2019. "Reduction of *Pseudomonas* Inoculated Into Whole Milk and Skin Milk by Ozonation." In *XXVI Brazilian Congress on Biomedical Engineering: CBEB 2018*, edited by R. Costa-Felix, J. Machado, and A. Alvarenga, 837–840. Springer.

Mzoughi, Z., I. Chakroun, S. B. Hamida, et al. 2017. "Ozone Treatment of Polysaccharides From *Arthrocnemum indicum*: Physico-Chemical Characterization and Antiproliferative Activity." *International Journal of Biological Macromolecules* 105: 1315–1323.

Nickhil, C., D. Mohapatra, A. Kar, S. K. Giri, U. S. Verma, and S. Muchahary. 2022. "Gaseous Ozone Treatment of Chickpea Grains: Effect on Functional Groups, Thermal Behavior, Pasting Properties, Morphological Features, and Phytochemicals." *Journal of Food Science* 87, no. 12: 5191–5207.

Nicola, S., G. Cocetta, A. Ferrante, and A. Ertani. 2022. "Fresh-Cut Produce Quality: Implications for Postharvest." In *Postharvest Handling*, edited by W. J. Florkowski, R. L. Shewfelt, S. E. Prussia, and N. H. Banks, 187–250. Academic Press.

Niveditha, A., R. Pandiselvam, V. A. Prasath, S. K. Singh, K. Gul, and A. Kothakota. 2021. "Application of Cold Plasma and Ozone Technology for Decontamination of Escherichia coli in Foods—A Review." *Food Control* 130: 108338.

O'Donnell, C., B. K. Tiwari, P. J. Cullen, and R. G. Rice. (Eds.). 2012. Ozone in Food Processing. https://doi.org/10.1002/9781118307472.

Osorio-Tejada, J., M. Escriba-Gelonch, R. Vertongen, A. Bogaerts, and V. Hessel. 2024. "CO_2 Conversion to CO via Plasma and Electrolysis: A Techno-Economic and Energy Cost Analysis." *Energy & Environmental Science* 17, no. 16: 5833–5853.

Özüiçli, M., A. Girişgin, A. Diker, Y. Baykalır, İ. Kısadere, and L. Aydın. 2023. "The Efficacy of Thyme, Peppermint, Eucalyptus Essential Oils, and Nanoparticle Ozone on Nosemosis in Honey Bees." *Kafkas Universitesi Veteriner Fakultesi Dergisi* 29, no. 4: 29167. http://doi.org/10.9775/kvfd.2023.29167.

Pandiselvam, R., R. Kaavya, Y. Jayanath, et al. 2020. "Ozone as a Novel Emerging Technology for the Dissipation of Pesticide Residues in Foods—A Review." *Trends in Food Science & Technology* 97: 38–54.

Pandiselvam, R., S. Subhashini, E. Banuu Priya, A. Kothakota, S. Ramesh, and S. Shahir. 2019. "Ozone Based Food Preservation: A Promising Green Technology for Enhanced Food Safety." *Ozone: Science & Engineering* 41, no. 1: 17–34.

Panigrahi, C., H. N. Mishra, and S. De. 2023. "Combined Ultrafiltration and Ozone Processing of Sugarcane Juice: Quantitative Assessment of Polyphenols, Investigation of Storage Effects by Multivariate Techniques and Shelf-Life." *Food Chemistry Advances* 2: 100214.

Park, M. K., J. Y. Cha, M. C. Kang, H. W. Jang, and Y. S. Choi. 2024. "The Effects of Different Extraction Methods on Essential Oils From Orange and Tangor: From the Peel to the Essential Oil." *Food Science & Nutrition* 12, no. 2: 804–814.

Parray, J. A., M. Y. Mir, N. Shafi, and A. K. Haghi. 2025. "Ozone Applications in Meat Processing and Seafood." In *Ozone Technology for Food Processing and Preservation*, edited by J. A. Parray, M. Y. Mir, N. Shafi, and A. K. Haghi, 55–76. Springer Nature Switzerland.

Pérez-Andrés, J. M., C. M. Charoux, P. J. Cullen, and B. K. Tiwari. 2018. "Chemical Modifications of Lipids and Proteins by Non-Thermal Food Processing Technologies." *Journal of Agricultural & Food Chemistry* 66, no. 20: 5041–5054.

Pérez-Lavalle, L., E. Carrasco, and A. Valero. 2020. "Strategies for Microbial Decontamination of Fresh Blueberries and Derived Products." *Foods* 9, no. 11: 1558.

Perez-Vazquez, A., M. Carpena, P. Barciela, L. Cassani, J. Simal-Gandara, and M. A. Prieto. 2023. "Pressurized Liquid Extraction for the Recovery of Bioactive Compounds From Seaweeds for Food Industry Application: A Review." *Antioxidants* 12, no. 3: 612.

Piechowiak, T., P. Antos, R. Józefczyk, P. Kosowski, K. Skrobacz, and M. Balawejder. 2019. "Impact of Ozonation Process on the Microbiological Contamination and Antioxidant Capacity of Highbush Blueberry (*Vaccinum corymbosum* L.) Fruit During Cold Storage." *Ozone: Science & Engineering* 41, no. 4: 376–385.

Piechowiak, T., K. Grzelak-Błaszczyk, M. Sójka, and M. Balawejder. 2022. "One-Time Ozone Treatment Improves the Postharvest Quality and Antioxidant Activity of *Actinidia arguta* Fruit." *Phytochemistry* 203: 113393.

Piechowiak, T., B. Skóra, and M. Balawejder. 2020. "Ozone Treatment Induces Changes in Antioxidative Defense System in Blueberry Fruit During Storage." *Food and Bioprocess Technology* 13: 1240–1245.

Pistón, M., I. Machado, E. Rodríguez-Arce, and I. Dol. 2021. "Development of an Ozone-Assisted Sample Preparation Method for the Determination of Cu and Zn in Rice Samples." *Journal of Analytical Methods in Chemistry* 2021, no. 1: 5586227.

Pogorzelska-Nowicka, E., M. Hanula, and G. Pogorzelski. 2024. "Extraction of Polyphenols and Essential Oils From Herbs With Green Extraction Methods—An Insightful Review." *Food Chemistry* 460: 140456.

Prabha, V., R. D. Barma, R. Singh, and A. Madan. 2015. "Ozone Technology in Food Processing: A Review." *Trends in Biosciences* 8, no. 16: 4031–4047.

Premjit, Y., N. U. Sruthi, R. Pandiselvam, and A. Kothakota. 2022. "Aqueous Ozone: Chemistry, Physiochemical Properties, Microbial Inactivation, Factors Influencing Antimicrobial Effectiveness, and Application in Food." *Comprehensive Reviews in Food Science and Food Safety* 21, no. 2: 1054–1085.

Purkait, M. K., P. Duarah, and P. P. Das. 2023. *Recovery of Bioactives From Food Wastes*. CRC Press.

Quintero, E. J., E. G. de León, J. Morán-Pinzón, A. Mero, E. León, and L. P. P. Cano. 2021. "Evaluation of the Leaf Extracts of Kalanchoe Pinnata and Kalanchoe Daigremontiana Chemistry, Antioxidant and Anti-Inflammatory Activity." *European Journal of Medicinal Plants* 32, no. 5: 45–54.

Radivojac, A., O. Bera, Z. Zeković, et al. 2021. "Extraction of Peppermint Essential Oils and Lipophilic Compounds: Assessment of Process Kinetics and Environmental Impacts With Multiple Techniques." *Molecules (Basel, Switzerland)* 26, no. 10: 2879.

Ribeiro, D. F., L. R. D. A. Faroni, M. A. G. Pimentel, L. H. F. Prates, F. F. Heleno, and E. R. De Alencar. 2022. "Ozone as a Fungicidal and Detoxifying Agent to Maize Contaminated With Fumonisins." *Ozone: Science & Engineering* 44, no. 1: 38–49.

Rice, R. G. 2012. "15 Health and Safety Aspects of Ozone Processing." In *Ozone in Food Processing*, edited by C. O'Donnell, B. K. Tiwari, P. J. Cullen, and Rip G. Rice. Blackwell Publishing Ltd. https://doi.org/10.1002/9781118307472.ch15.

Rodrigues Machado, A., T. Atatoprak, J. Santos, et al. 2023. "Potentialities of the Extraction Technologies and Use of Bioactive Compounds From Winery By-Products: A Review From a Circular Bioeconomy Perspective." *Applied Sciences* 13, no. 13: 7754.

Ronie, M. E., A. H. A. Aziz, R. Kobun, et al. 2024. "Unveiling the Potential Applications of Plant By-Products in Food–A Review." *Waste Management Bulletin* 2: 183–203.

Rosal, R., A. Rodríguez, J. A. Perdigón-Melón, et al. 2010. "Degradation of Carbamazepine, Diclofenac and Ibuprofen in Water by Ozonation and Advanced Oxidation Processes." *Chemosphere* 82, no. 3: 495–501. https://doi.org/10.1016/j.chemosphere.2010.10.019.

Rosen, Y., H. Mamane, and Y. Gerchman. 2019. "Short Ozonation of Lignocellulosic Waste as Energetically Favorable Pretreatment." *Bioenergy Research* 12: 292–301.

Rosen, Y., H. Mamane, and Y. Gerchman. 2021. "Immersed Ozonation of Agro-Wastes as an Effective Pretreatment Method in Bioethanol Production." *Renewable Energy* 174: 382–390.

Sachadyn-Król, M., and S. Agriopoulou. 2020. "Ozonation as a Method of Abiotic Elicitation Improving the Health-Promoting Properties of Plant Products—A Review." *Molecules (Basel, Switzerland)* 25, no. 10: 2416. https://doi.org/10.3390/molecules25102416.

Sachadyn-Król, M., M. Materska, B. Chilczuk, et al. 2016. "Ozone-Induced Changes in the Content of Bioactive Compounds and Enzyme Activity During Storage of Pepper Fruits." *Food Chemistry* 211: 59–67.

Sharma, V. K., and N. J. D. Graham. 2010. "Oxidation of Amino Acids, Peptides and Proteins by Ozone: A Review." *Ozone: Science & Engineering* 32, no. 2: 81–90. https://doi.org/10.1080/01919510903510507.

Dos Santos, F. K. F., I. G. C. Barcellos-Silva, O. Leite-Barbosa, R. Ribeiro, Y. Cunha-Silva, and V. F. Veiga-Junior. 2024. "High Added-Value By-Products From Biomass: A Case Study Unveiling Opportunities for Strengthening the Agroindustry Value Chain." *Biomass* 4, no. 2: 217–242.

Saputera, W. H., A. S. Putrie, A. A. Esmailpour, D. Sasongko, V. Suendo, and R. R. Mukti. 2022. "Technology Advances in Phenol Removals: Current Progress and Future Perspectives." *Catalysts* 11, no. 8: 998.

Saravana, P. S., V. Ummat, P. Bourke, and B. K. Tiwari. 2023. "Emerging Green Cell Disruption Techniques to Obtain Valuable Compounds From Macro and Microalgae: A Review." *Critical Reviews in Biotechnology* 43, no. 6: 904–919.

Senatore, V., G. Oliva, T. Zarra, V. Belgiorno, and V. Naddeo. 2019. "Bio-Scrubber Coupled With Ozonation for Enhanced VOCs Abatement." Paper presented at the 16th International Conference on Environmental Science and Technology, Rhodes, Greece, September 4–7.

Serapiglia, M. J., K. D. Cameron, A. J. Stipanovic, and L. B. Smart. 2022. "Ozone-Induced Changes in Phenylpropanoid Metabolism and Antioxidant Responses in Barley Seedlings." *International Journal of Molecular Sciences* 23, no. 1: 314. https://doi.org/10.3390/ijms23010314.

Seridou, P., and N. Kalogerakis. 2021. "Disinfection Applications of Ozone Micro-and Nanobubbles." *Environmental Science: Nano* 8, no. 12: 3493–3510.

Shafiee, Z., and B. H. Samani. 2024. "The Effects of Ozone Pretreatment on the Physicochemical, Functional, Bioactive, Textural, and Sensory Properties of Medicinal Plants: A Comprehensive Review." *Future Natural Products* 10, no. 1: 30–38.

Shah, N. N. A. K., A. Sulaiman, N. S. M. Sidek, and N. A. M. Supian. 2019. “Quality Assessment of Ozone-Treated Citrus Fruit Juices.” *International Food Research Journal* 26, no. 5: 1405–1415.

Shah, N. N. A. K., N. A. M. Supian, and N. A. Hussein. 2019. “Disinfectant of pummelo (*Citrus grandis* L. Osbeck) Fruit Juice Using Gaseous Ozone.” *Journal of Food Science and Technology* 56, no. 1: 262–272. https://doi.org/10.1007/s13197-018-3486-2.

Shynkaryk, M. V., T. Pyatkovskyy, H. M. Mohamed, A. E. Yousef, and S. K. Sastry. 2015. “Physics of Fresh Produce Safety: Role of Diffusion and Tissue Reaction in Sanitization of Leafy Green Vegetables With Liquid and Gaseous Ozone-Based Sanitizers.” *Journal of Food Protection* 78, no. 12: 2108–2116.

Simpson, A. M. A., and W. A. Mitch. 2022. “Chlorine and Ozone Disinfection and Disinfection Byproducts in Postharvest Food Processing Facilities: A Review.” *Critical Reviews in Environmental Science and Technology* 52, no. 11: 1825–1867.

Singh, A. A., A. Ghosh, M. Agrawal, and S. B. Agrawal. 2023. “Secondary Metabolites Responses of Plants Exposed to Ozone: An Update.” *Environmental Science and Pollution Research* 30, no. 38: 88281–88312.

Sivaranjani, S., V. A. Prasath, R. Pandiselvam, A. Kothakota, and A. M. Khaneghah. 2021. “Recent Advances in Applications of Ozone in the Cereal Industry.” *LWT* 146: 111412.

Skoczko, I. 2025. “Energy Efficiency Analysis of Water Treatment Plants: Current Status and Future Trends.” *Energies* 18, no. 5: 1086.

Sonkar, R. M., P. S. Gade, V. Bokade, S. N. Mudliar, and P. Bhatt. 2021. “Ozone Assisted Autohydrolysis of Wheat Bran Enhances Xylooligosaccharide Production With Low Generation of Inhibitor Compounds: A Comparative Study.” *Bioresource Technology* 338: 125559.

Subroto, E., F. Filianty, R. Indiarto, and A. Andita Shafira. 2022. “Physicochemical and Functional Properties of Modified Adlay Starch (*Coix lacryma-jobi*) by Microwave and Ozonation.” *International Journal of Food Properties* 25, no. 1: 1622–1634.

Tahamolkonan, M., A. M. Ghahsareh, M. K. Ashtari, and N. Honarjoo. 2022. “Tomato (*Solanum lycopersicum*) Growth and Fruit Quality Affected by Organic Fertilization and Ozonated Water.” *Protoplasma* 259, no. 2: 291–299.

Tanou, G., I. S. Minas, E. Karagiannis, et al. 2015. “The Impact of Sodium Nitroprusside and Ozone in Kiwifruit Ripening Physiology: A Combined Gene and Protein Expression Profiling Approach.” *Annals of Botany* 116, no. 4: 649–662.

Tian, Y., and Q. Kamran. 2023. “Creating Value for Sustainability by Transforming the Food Well-Being Paradigm—Alternative New Food Product Development.” *Journal of Creating Value* 9, no. 2: 291–308.

Torres-Valenzuela, L. S., A. Ballesteros-Gómez, and S. Rubio. 2020. “Green Solvents for the Extraction of High Added-Value Compounds From Agri-Food Waste.” *Food Engineering Reviews* 12: 83–100.

Travaini, R., J. Martín-Juárez, A. Lorenzo-Hernando, and S. Bolado-Rodríguez. 2016. “Ozonolysis: An Advantageous Pretreatment for Lignocellulosic Biomass Revisited.” *Bioresource Technology* 199: 2–12.

Tripathi, S. K., N. K. Bhardwaj, and H. Roy Ghatak. 2020. “Developments in Ozone-Based Bleaching of Pulps.” *Ozone: Science & Engineering* 42, no. 2: 194–210.

Twi-Yeboah, N., D. Osei, W. H. Dontoh, G. A. Asamoah, J. Baffoe, and M. K. Danquah. 2024. “Enhancing Energy Efficiency and Resource Recovery in Wastewater Treatment Plants.” *Energies* 17, no. 13: 3060.

Üner Öztürk, K., and M. A. Koyuncu. 2021. “Effects of Ozone and Salicylic Acid on Post-Harvest Quality of Parsley During Storage.” *Biological Agriculture & Horticulture* 37, no. 3: 183–196.

Vladić, J., M. Jakovljević Kovač, V. Pavić, et al. 2023. “Towards a Greener Approach for Biomass Valorization: Integration of Supercritical Fluid and Deep Eutectic Solvents.” *Antibiotics* 12, no. 6: 1031.

Vlotman, D. E., D. Key, and B. J. Bladergroen. 2022. “Technological Advances in Winery Wastewater Treatment: A Comprehensive Review.” *South African Journal of Enology and Viticulture* 43, no. 1: 58–80.

Wang, T., L. Zhu, L. Mei, and H. Kanda. 2024. “Extraction and Separation of Natural Products From Microalgae and Other Natural Sources Using Liquefied Dimethyl Ether, a Green Solvent: A Review.” *Foods* 13, no. 2: 352.

Wang, Y., L. Chen, J. Jiang, and Y. Gong. 2019. “Effect of Ozone Treatment on Antioxidant Activity and Phenolic Compounds in Strawberry Fruit During Storage.” *RSC Advances* 9, no. 13: 7328–7336. https://doi.org/10.1039/C8RA10140H.

Wei, C., F. Zhang, Y. Hu, C. Feng, and H. Wu. 2017. “Ozonation in Water Treatment: The Generation, Basic Properties of Ozone and Its Practical Application.” *Reviews in Chemical Engineering* 33, no. 1: 49–89.

Wen, L., Z. Zhang, D. W. Sun, S. P. Sivagnanam, and B. K. Tiwari. 2020. “Combination of Emerging Technologies for the Extraction of Bioactive Compounds.” *Critical Reviews in Food Science and Nutrition* 60, no. 11: 1826–1841.

Xiao, W., H. Zhang, X. Wang, et al. 2022. “Interaction Mechanisms and Application of Ozone Micro/Nanobubbles and Nanoparticles: A Review and Perspective.” *Nanomaterials* 12, no. 12: 1958.

Xue, W., J. Macleod, and J. Blaxland. 2023. “The Use of Ozone Technology to Control Microorganism Growth, Enhance Food Safety and Extend Shelf Life: A Promising Food Decontamination Technology.” *Foods* 12, no. 4: 814.

Yaseen, T. 2019. “Invasive Pests That Threaten Strategic Agricultural Crops in the Arab and Nena Region.” *New Medit* 18, no. 4: 117–130.

Ye, Z., Z. Wang, J. Wang, Y. Li, and Y. Luo. 2020. “Ozone Treatment Affects Phenolic Metabolism and Antioxidant Activity of Harvested Blueberries (*Vaccinium corymbosum* L.).” *Food and Bioprocess Technology* 13: 519–530. https://doi.org/10.1007/s11947-019-02395-w.

Zhang, C., L. Zhao, W. Li, J. Ren, H. Wang, and B. He. 2024. “The Limitation of Unproductive Binding of Cellulases to Lignin by Ozone Pretreatment.” *Applied Sciences* 14, no. 6: 2318.

Zhang, D., B. Jiang, Y. Luo, et al. 2022. “Effects of Ultrasonic and Ozone Pretreatment on the Structural and Functional Properties of Soluble Dietary Fiber From Lemon Peel.” *Journal of Food Process Engineering* 45, no. 1: e13916.

Zhang, K., J. Liu, H. Lv, et al. 2025. “Advances in Ozone Technology for Environmental, Energy, Food and Medical Applications.” *Processes* 13, no. 4: 1126. https://doi.org/10.3390/pr13041126.

Zhou, Z., S. Zuber, F. Cantergiani, I. Sampers, F. Devlieghere, and M. J. F. i. V. S. Uyttendaele. 2018. “Inactivation of Foodborne Pathogens and Their Surrogates on Fresh and Frozen Strawberries Using Gaseous Ozone.” *Frontiers in Sustainable Food Systems* 2: 51.

Zhu, X., J. Jiang, C. Yin, G. Li, Y. Jiang, and Y. Shan. 2019. “Effect of Ozone Treatment on Flavonoid Accumulation of Satsuma Mandarin (Citrus Unshiu Marc.) During Ambient Storage.” *Biomolecules* 9, no. 12: 821. https://doi.org/10.3390/biom9120821.

Ziyaina, M., and B. Rasco. 2021. “Inactivation of Microbes by Ozone in the Food Industry: A Review.” *African Journal of Food Science* 15, no. 3: 113–120.