Journal of Agriculture and Value Addition
June 2025, Vol. 8(1): 1-19
DOI: https://doi.org/10.4038/java.v8i1.161

INVITED REVIEW

Recent Advances in Green Technologies for Sustainable Food Preservation: A Review

M.P. Piyasena[1], S.D.N. Kaushalya[2], W.A.J.P. Wijesinghe[2]*

[1]*Department of Export Agriculture, Uva Wellassa University, Badulla 90000, Sri Lanka.*
[2]*Department of Food Science and Technology, Uva Wellassa University, Badulla 90000, Sri Lanka.*

Submitted: May 28, 2024; Revised: April 09, 2025; Accepted: May 16, 2025
*Correspondence: janakaw@uwu.ac.lk, https://orcid.org/0000-0002-0621-534X

ABSTRACT

As a key driver of the global economy, the food industry relies on food preservation technologies not only to minimize food losses, but also to align with global sustainability efforts such as promoting food security, reducing waste, and mitigating environmental impact. Additionally, the deterioration of food quality and the negative health impacts associated with synthetic additives have prompted the food industry to research alternative food preservation techniques. In this context, green technologies in food preservation serve as a promising solution providing ecological, economical, and innovative approaches. Hence, this review aims to examine recent advances in sustainable food preservation techniques and their role in improving food safety and extending shelf life. Ozone-based preservation, encapsulated essential oils, curcumin-based photosensitization, chitosan-based coatings and films, and the use of algae as preservatives are currently employed viable green technologies that manifest effective antimicrobial properties, extended shelf life, absence of toxic chemical residues, and preserved natural properties. By preserving food safety, nutritional quality, and appealing sensory properties, green technologies not only meet dynamic and evolving consumer preferences but also promote sustainability and eco-friendliness within the food industry. Further developments and optimization of these green technologies could transform food preservation by offering sustainable alternatives to conventional methods while creating new insights for research to enhance food safety and food security.

Keywords: *Food preservation, Food safety, Green technologies, Sustainable*

INTRODUCTION

Food stands as one critical component in the achievement of the United Nations' second Sustainable Development Goal (SDG 2) which intends to 'end hunger, achieve food security, improve nutrition and promote sustainable agriculture. To reach this goal, nations implement different approaches to food production, storage, transport, distribution, and marketing focusing on reducing inefficiencies, food loss, and waste (United Nations, 2023). Addressing postharvest losses, food spoilage, and inefficiencies in food systems which together contribute to food insecurity are key challenges to be addressed to fulfil SDG 2 where food preservation comes into play as a viable solution for minimizing food waste and sustainable use of food resources. Enhancing food availability and stability by extending the shelf life of perishables, maintaining their nutritional value, and reducing reliance on excessive food production through strategic food preservation techniques supports fulfilling SDG 2.

Food preservation can be defined as the process of treating and handling food in ways that inhibit, prevent or delay food spoilage, deterioration, and food loss by maintaining internal and external factors, thereby extending the shelf life of food while maintaining their nutritional and sensory quality (Amit *et al.*, 2017). The history of food preservation runs about 3.4 million years back (Knorr and Augustin, 2023). Food preservation techniques have undergone significant evolution over time from ancient methods such as drying, salting, and fermentation to advanced modern approaches through scientific and technological innovations. The conventional methods of food preservation include thermal processing, cooling, freezing, water activity reduction, fermentation, and hurdle technology (Augusto *et al.*, 2018). Later on, modern food preservation techniques such as vacuum packing, irradiation, smoking, use of chemical food additives, and canning came into use in the food industry (Shajil *et al.*, 2018). All these preservation methods focus on controlling or inhibiting microbial proliferation, enzymatic reactions, chemical reactions, or physical factors leading to food deterioration (Joardder and Masud, 2019).

In recent years, the food industry, in particular, has been efficiently embracing 'green approaches' in response to the emerging paradigm for environmental friendliness, sustainable use of natural resources, reduced use of energy, and use of renewable sources. The approaches can vary from policies and regulations to innovative green designs of products, raw materials, energy, or green innovative production processes. Amid different industries, the food industry is identified as a leading adopter of green technologies, automatically shifting to green approaches to food processing particularly for minimizing environmental footprint through minimal synthetic food additives, reduced energy consumption, and incorporation of renewable and biodegradable resources (Zhang *et al.*, 2020).

Though conventional food preservation methods such as chilling, freezing, pasteurization, sterilization, acidification, water activity reduction, drying, dehydration, fermentation, and use of antimicrobials remain prevalent, they are associated with several food safety issues mainly including the survival of pathogenic microorganisms, formation of harmful chemical by-products, and the potential development of antimicrobial-resistant microbial strains (Pandiselvam *et al.*, 2019; Ogwu *et al.*, 2024). Consequently, the food industry is actively seeking sustainable yet efficient and economical alternative food preservation strategies. This transformation is further fueled by the consumer demand for chemical additives-free organic foods and the increased consumer awareness about the health issues correlated with the use of synthetic food, collectively encouraging a shift towards greener food preservation technologies (Fernando *et al.*, 2024).

All in all, green food preservation refers to the use of environmentally sustainable, non-toxic, and energy-efficient methods to extend the shelf life of food while maintaining their nutritional value, sensory quality, and safety. Ozone-based preservation, encapsulated essential oils, curcumin-based photosensitization, chitosan-based coatings and films, and the use of algae as preservatives are examples for currently applied green technologies in food preservation. These methods have exhibited significant improvements and optimizations over the last five years aligning well with principles of 'green' technology concepts. This review paper aims to provide a comprehensive analysis of these emerging green preservation technologies assessing their mechanisms of action, applications, advantages, limitations, and future perspectives.

Ozone-based food preservation

Ozone (O_3) is a trioxygen molecule formed from atmospheric oxygen through the action of electrical discharge, ultraviolet irradiation, or electrochemical processes. It is considered a strong antimicrobial agent in the food industry (Lone *et al.*, 2019; Botondi *et al.*, 2021). During the production of ozone, diatomic oxygen molecules split into highly reactive singlet oxygen species, which then react with other oxygen molecules to form triatomic ozone molecules with high oxidation potential (Sarron *et al.*, 2021).

The application of ozone in food preservation can be identified as an effective and timely technique, due to its rapid decomposition which leaves no residual effects on the environment (Pandiselvam *et al.*, 2017). Therefore, ozone can be pinpointed as a viable green alternative to existing traditional disinfectants in the food industry, suitable for preservation and extension of the shelf life of a wide range of food commodities. In 1997, the US Food and Drug Administration (FDA) accorded Generally Recognized As Safe (GRAS) status for ozone. Later, in June 2001, the US FDA formally approved the use of ozone as an antimicrobial agent for the treatment, storage, and processing of foods (Pandiselvam *et al.*, 2019).

The application of ozone treatment in the food industry is versatile, and it is commonly used for disinfecting processing plants, processing equipment, and surfaces, water decontamination, and degradation of pesticide residues (Pawar *et al.*, 2021; Freitas-Silva *et al.*, 2024). Apart from that, the preservation of food commodities through ozone treatment has gained attention at present, due to its prominent antimicrobial effects.

When considering the mechanism of ozone-based food preservation, two primary mechanisms are involved in the inhibition of microbial growth. In the first mechanism, ozone acts as a potent oxidizer and oxidizes the microbial cell structures, particularly cell membranes resulting in disruption of structures thereby leading to microbial cell death (Fan, 2021). In the second mechanism, hydroxyl radicals, produced by the auto-decomposition of ozone molecules rapidly react with components in the cell envelope, nucleic materials, and intracellular enzymes of microorganisms causing oxidative bursts and ultimately inactivating the microorganisms (Pandiselvam *et al.*, 2017). Both of these mechanisms cause the elimination of microorganisms from the food matrix, extending the shelf life of the products.

Previous studies have demonstrated the antimicrobial effect of ozone over a wide spectrum of microorganisms, including food-borne pathogenic bacteria such as *Escherichia coli*, *Salmonella*, and *Listeria monocytogenes*, fungi including *Candida albicans*, *Zygosaccharomyces bacilli*, *Alternaria*, *Aspergillus flavus*, and *Aspergillus parasiticus*, protozoa such as *Cryptosporidium* and *Giardia*, and many viruses (Pawar *et al.*, 2021; Pandiselvam *et al.*, 2019). In addition, according to Xue *et al.* (2023), ozone treatment has shown effectiveness against bacterial and fungal spores, including spores of *Bacillus*, *Coliform*, *Micrococcus*, *Flavobacterium*, *Alcaligenes*, *Serratia*, *Aspergillus*, and *Penicillium*.

In ozone-based food preservation, ozone can be applied to food commodities either in gaseous form or in aqueous form (Fan, 2021). According to previous studies and reviews, both forms of ozone have shown positive outcomes in extending the shelf life and maintaining the quality of a variety of food commodities including fresh fruits and vegetables, grains, poultry, meat products, and dairy products (Pawar *et al.*, 2021).

In the fruit and vegetable industry, aqueous ozone is commonly used as a less hazardous postharvest treatment or microbial safety control method for intact or fresh-cut fruits and vegetables during storage (Xue *et al.*, 2023). Ozonated water is primarily applied to rinse fruits and vegetables as an alternative to traditional sterilizing agents (Botondi *et al.*, 2021). According to Sarron *et al.* (2021), a significant reduction in total mesophilic aerobic bacteria, yeasts and moulds, coliforms, *E. coli*, and *Salmonella enteritidis* was observed following liquid ozone treatment of fresh carrots. Meanwhile, the application of gaseous ozone at 1–5 mg/L, for 9.5–110.5 min was found to increase the shelf life of freshly stored carrots. Lone *et al.* (2019) observed a reduction of bacterial count in kiwi fruits from 1.5×10^8 to 1.2×10^2 CFU/mL concluding that ozone treatment is a successful method to preserve fruits and enhance the shelf life during postharvest storage. In another study, 2.4 mg/L aqueous ozone application for 5 min significantly reduced the microbial load on shredded green bell peppers leading to prolonged shelf life and maintaining organoleptic properties for 6 d longer than the control samples (Ummat *et al.*, 2018).

Spoilage of meat and meat products is primarily associated with microbial activity, and ozone treatment has shown positive responses over fresh carcasses, processed meat, and other meat products. Using ozone as an alternative to chlorine in sanitizing chicken carcasses has shown effective control of *Salmonella*, *Staphylococci*, *E. coli* populations and total coliform counts (Khanashyam *et al.*, 2022). According to a previous study, spraying ozonated water on decontamination of beef carcasses at a 95 mg/L rate has significantly reduced the pathogen count, compared to carcasses washed with plain water

(Pandiselvam *et al.*, 2019). According to Ayranci *et al.* (2020), gaseous ozone treatment at 0.01 kg/m^3 for up to 8 h on turkey meat showed 2.9, 2.3, and 1.9 log reductions in total aerobic mesophilic bacteria, *Enterobacteriaceae*, and yeast respectively.

The dairy sector is another industry that utilizes ozone treatments to ensure safety and extend the shelf life of milk and milk-based products such as cheese and yoghurt. According to previous studies, fluid milk treated with 0.2 g/L ozone for 5, 10, and 15 min, achieved complete inactivation of *L. monocytogenes* by the end of 15 min (Khanashyam *et al.*, 2022). A recent study evaluated the possibility of using ozone treatment as a substitute for the pasteurization of milk and concluded that ozonation can be utilized as an alternative to conventional thermal treatments such as pasteurization of fluid milk (Khanashyam *et al.*, 2022). A shelf-life study has been done for cheese by ozonating the atmosphere at a rate of 5-7 μg/L and exposing them for at least 4 h in 3-day intervals. There, the storage life of cheese was increased by up to 4 months whereas mould growth appeared within a month in the control sample (Pandiselvam *et al.*, 2019).

As a green food preservation technique, ozone-based food preservation technology is a boon to the food industry due to its advantageous characteristics over conventional food preservation methods. The primary advantage of ozone treatment is its non-residual nature. In contrast to the chemical methods which leave residual compounds that may tend to possess carcinogenic impacts on human health, ozone treatment remains free of chemical residues (Brodowska *et al.*, 2018). For example, some European countries have prohibited the use of antimicrobial solutions such as chlorinated water in fresh fruit and vegetable disinfection, due to its ability to develop by-products that are cytotoxic to mammalian cells, mutagenic, and persistent in the environment (Sarron *et al.*, 2021). In this context, ozone-based treatment has become an attractive choice in food preservation due to its rapid action, potent oxidative characteristics, inactivation of microorganisms at relatively low concentrations, and quick auto-decomposition without leaving any hazardous halogenated compounds making it an environment-friendly, green technology. Furthermore, the energy requirement for ozone treatment is much lower than that of radiation and thermal treatments (Pandiselvam *et al.*, 2019).

However, higher ozone concentrations may negatively affect the sensory properties of the foods ultimately reducing the overall food quality (Pawar *et al.*, 2021). According to Vashisht *et al.* (2024), fat-rich dairy products, such as cream milk are more prone to lipid peroxidation during ozone treatment which can lead to the deterioration of colour attributes upon high exposure time and ozone doses. Additionally, excessive exposure to ozone may cause ozone toxicity in humans, affecting human health (Afsah-Hejri *et al.*, 2020). The effectiveness of the process depends on ozone concentration, exposure time, and temperature (Afsah-Hejri *et al.*, 2020). Nevertheless, ozone-based food preservation can be considered a viable and 'greener' alternative to existing traditional food preservation techniques.

Encapsulated essential oils

Essential oils are a group of secondary metabolites of plants with excellent antimicrobial activity and antioxidant capacity (Zhang *et al.*, 2023). As consumers are increasingly demanding food products with natural additives with natural antimicrobial properties, essential oils from herbs and spices play a crucial role in the food industry as alternatives to synthetic food preservatives (Munasinghe *et al.*, 2022). However, high volatility, low stability, high susceptibility to environmental conditions, strong organoleptic characteristics, and low solubility in water due to the hydrophobic nature are the major limitations of directly incorporating essential oils into food systems (Prakash *et al.*, 2018; Reis *et al.*, 2022). Therefore, encapsulating essential oils in a suitable delivery system to increase their dispersibility in low-fat foods and thereby enhancing their antimicrobial activity, has gained interest in the food industry as a viable approach to overcome the above issues (Reis *et al.*, 2022).

In general, encapsulation is a technique of entrapping bioactive substances in a protective wall material from the nanometer or micrometre to millimetre range and enables a more stable and gradual release of bioactive substances (Liao *et al.*, 2021). All microencapsulation techniques are based on three basic principles; formation of a wall around the core material, keeping the core materials inside the capsule without any release of the content, and releasing the core material at the precise rate and time (Macías-Cortés *et al.*, 2020). Encapsulation techniques can be divided into two main categories as physical and chemical techniques. Physical encapsulation methods do not undergo polymerization reactions to obtain microcapsules, instead they microcapsule through mechanical processes. In contrast, chemical methods create microcapsules through polymerization reactions involving precursor materials. Physical methods include extrusion, fluidization, lyophilization, spray drying, and supercritical fluid extraction while coacervation, ionic gelation, liposomes, and mini-emulsion polymerization are primary chemical encapsulation methods. Different encapsulation techniques offer different advantages and disadvantages. Lyophilization is suitable for encapsulating heat-sensitive substances, extrusion helps to avoid degradation of compounds due to lower temperature and spray drying offers a greater efficiency in encapsulation compared to other techniques. Liposomes act as an efficient protector of water-soluble active ingredients, while ionic gelation has a low cost and high encapsulation efficiency (Reis *et al.*, 2022). The selection of the most suitable wall material is one crucial determinant of a successful encapsulation process. Various wall materials are used for microencapsulation in food systems, including polysaccharides, lipids, and proteins (Macías-Cortés *et al.*, 2020).

Recently, natural plant essential oils, such as those of oregano, clove, basil, cinnamon, thyme, peppermint, rosemary, citrus, tea tree, and ginger along with their monomeric components have demonstrated effectiveness in preserving foods (Zhang *et al.*, 2023). Encapsulated essential oils have currently been implemented as a green preservative in the food industry, particularly in the fruit and vegetable sector, meat and meat products, seafoods and dairy products among others (Table 1) (Yang *et al.*, 2023; Zhang *et al.*, 2023).

Table 1: Application of encapsulated essential oils in fruits, vegetables, meat, seafood and dairy products

Type of treatment	Type of food	Major effect	References
Encapsulated clove essential oil nanoparticles	Minimally processed pomegranate arils	Extended the aril shelf life for 54 d compared to the arils treated with pure clove essential oil which became unusable on the 18^{th} d	(Hasheminejad and Khodaiyan, 2020)
Microencapsulated thyme oil	Minimally processed lettuce	Showed higher microbiological quality, organoleptic quality, and extended shelf life than the free thyme oil-treated samples	(Viacava *et al.*, 2018)
Encapsulated essential oil of *Heracleum persicum* fruit in chitosan nanoparticles	Sweet bell pepper	Showed an overall acceptability up to the 24^{th} d of storage, while the untreated samples lost their acceptability on the 18^{th} d of storage	(Taheri *et al.*, 2020)
Nano-encapsulated thyme essential oil entrapped in a chitosan matrix	Fresh pork	60.35% inhibition on gram-positive bacteria such as *Staphylococcus aureus*, and 55.50% inhibition on gram-negative bacteria such as *E. coli*	(Ojeda-Piedra *et al.*, 2022)
Nano-encapsulated lemon essential oil	Fish burgers	Extended the shelf life of burgers and protected from undesirable chemical and sensory alterations	(Hasani *et al.*, 2020)
Encapsulated *Nepeta hormozganica* and *Nepeta Dschuprensis* essential oils in chitosan nanoparticles	Shrimps	Increased antifungal efficiency by up to 100% against *Fusarium oxysporium, Sclerotinia sclerotiorum, Pythium aphanidermatum, Alternaria alternata, Rhizactonia Solani,* and *Botrytis cinerea*	(Amighi *et al.*, 2023)
Thyme essential oil microcapsules	Fresh milk	Extended the shelf life of milk, while showing inhibitory effects on *Bacillus subtilis*, *S. aureus*, and *E. coli*	(Zhang *et al.*, 2019)
Scent leaf (*Ocimum gratissimum*) essential oil microcapsules	Soy-based yoghurt	Showed no bacterial count by d 3 and 3.62×10^6 CFU/100 mL by d 5, while control samples showed 15.67×10^6 CFU/100 mL by d 3 and 43.33×10^6 CFU/100 mL by d 5	(Olabiran *et al.*, 2023)

Curcumin-based photosensitization

Photosensitization, or photodynamic inactivation is a recently emerged, promising green alternative to conventional preservation techniques in the food industry. It is a non-thermal, light-based sterilization technology where the mechanism involves three major components: a natural photosensitizer, illumination, and oxygen (Dias *et al.*, 2020). Generally, a photosensitizer can be defined as a chemical component with the ability to absorb photons at a specific wavelength and reach a new electronic state known as the excited state that can react with itself or a second molecule (Damyeh *et al.*, 2019). Illumination or exposure to light at a predefined wavelength causes the activation of photosensitizer. Excited photosensitizer molecules transfer the excessive electrons/hydrogen or energy to surrounding substances, resulting in the generation of reactive oxygen species. The produced reactive oxygen species interact with microbial proteins, lipids, and nucleic acids, and cause oxidative damage to essential cellular components, triggering the death of all microbial cells (Damyeh *et al.*, 2020).

Curcumin, a polyphenolic compound derived from the rhizomes of *Curcuma longa* L. is renowned as one of the strongest natural photosensitizers. Curcumin has gained attention as a food-grade photosensitizer with its excellent antimicrobial properties and photosensitivity (Yu *et al.*, 2022). The promising phototoxicity of curcumin as a natural photosensitizer has extensively been studied against a wide range of microorganisms that challenge the food industry. It is efficient against a wide spectrum of microorganisms such as Gram-negative and Gram-positive bacteria including *Listeria monocytogenes*, *Vibrio parahaemolyticus*, *E. coli, Salmonella typhimurium, Staphylococcus aureus, Listeria innocua*, fungal spores such as *Aspergillus flavus, Aspergillus niger, Penicillium griseofulvum, Penicillium chrysogenum, Fusarium oxysporum*, and yeasts like *Candida albicans, Candida glabrata*, and *Candida dubliniensis* (Damyeh *et al.*, 2020).

The applicability of curcumin-based photosensitization has been investigated using both fresh and processed products. It has shown effective control against microbial spoilage of a vast range of food with no adverse effects on the organoleptic quality of the food product. Tao *et al.* (2019) investigated the effect of curcumin-mediated photosensitization on the storage quality of fresh-cut Fuji apples inoculated with *E. coli*. The results of the study showed a reduction in *E. coli* population on the surface of apple slices at a reduced level of 0.95 log (Tao *et al.*, 2019). The combination of curcumin and illumination during the storage of fresh-cut pineapple at 4°C showed suppressed growth of *E. coli* with a reduction of 0.19-1.24 log and controlled browning in fresh-cut pineapple (Zou *et al.*, 2021). According to the findings of the study conducted by Lin *et al.* (2019), illumination of fresh-cut Hami melon with 50 μmol/L curcumin for 60 min using a blue LED lamp has reduced the total aerobic bacterial count from 6.81 to 4.95 (log CFU/g).

Also, compared to the control group, photodynamic sterilization has effectively delayed the browning rate and maintained the luminosity, firmness, water content, and soluble solids content of fresh-cut Hami melon, preserving the sensory quality during 9 days of cold storage. Previous studies have shown that the efficacy of curcumin-based photosensitization may depend on several factors such as the curcumin concentration and the light dose. Damyeh *et al.* (2019) demonstrated the concentration-dependent behaviour of curcumin-based photosensitization upon the shelf life of fresh dates, where 1400 µM curcumin was efficient in delaying mould spoilage of fresh dates. Investigation of the shelf life and quality of pacific oysters during storage at 5°C showed a 8–12 d prolonged shelf life (Liu *et al.*, 2016). Additionally, the curcumin range of 25–75 µM and a light dose of 114.5 J/cm^2 were able to effectively inactivate *A. flavus* spores and prolong the shelf-life of peanuts by seven days (Mukubesa *et al.*, 2022). As per the investigation conducted by Huang *et al.* (2021) on the effect of curcumin-mediated photodynamic inactivation (PDI) on preserving the quality of salmon contaminated with *L. monocytogenes* showed that PDI decelerated the proliferation of *L. monocytogenes* on salmon during storage at 25°C, with 99.99% inhibition reaching 4.0 $\log_{10}$ CFU/g compared to the control. Moreover, PDI greatly retarded the increase in pH ($p<0.05$), slowed the accumulation of free fatty acids, and decelerated the degradation of proteins, ultimately preserving the high nutritional value of the salmon (Huang *et al.*, 2021).

Curcumin-based photosensitization has gained significant attention in the food industry as an advantageous green food preservation technique, primarily due to its promising antimicrobial efficacy against a broad spectrum of food spoilage microorganisms. It also helps to protect the organoleptic quality of the foods, is readily available, cost-effective, and safe even with high doses (Munir *et al.*, 2022). Furthermore, low energy consumption and environmental friendliness make curcumin-based photosensitization a sustainable preservation technique (Munir *et al.*, 2022).

Chitosan-based coatings and films

Due to the rapid increase in consumer awareness regarding the health issues concomitant with the use of synthetic agents for the preservation of food products, the food industry has now driven towards the use of 'greener' food preservation methods (Fernando *et al.*, 2024). Together with that, serious contamination issues associated with the excessive use of plastic in the food industry have fostered the use of renewable and natural compounds with bioactive properties to control, inhibit, or prevent the growth of microorganisms and thereby preserve the quality of the product (Butnaru *et al.*, 2019; Muñoz-Tebar *et al.*, 2023). Currently, biopolymers have grabbed greater attention with this growing demand and natural biopolymers such as chitosan are gaining interest in the food industry along with their specific characteristics such as biological origin, biodegradability, biocompatibility, availability, non-toxicity, and film-forming properties (Fernando *et al.*, 2024).

Chitosan is one of the most ubiquitous natural bioactive polysaccharides, naturally found in the exoskeletons of molluscs and crustaceans, and cuticles of fungi and insects (Zárate-Moreno *et al.*, 2023; Fernando *et al.*, 2024). It is a compound with a complex chemical structure formed by randomly distributed D-glucosamine units and N-acetylglucosamine units linked by β-(1-4) glycosidic bonds (Butnaru *et al.*, 2019). Chitosan as a bioactive polysaccharide exhibits intrinsic antimicrobial properties and has been recognized as a natural alternative to chemically synthesized antimicrobial polymers with its exceptional physicochemical properties imparted by the polysaccharide backbone (Broek *et al.*, 2015). Implementation of chitosan in food systems can be primarily achieved through the direct coating of food surfaces or forming antimicrobial films to package foods (Yu *et al.*, 2022).

Chitosan-based coatings and films play multifaceted preservative mechanisms (Figure 1) including the antimicrobial mechanism. Several action mechanisms have been suggested to explain the antimicrobial activity of chitosan films in preserving foods. According to previous studies, the major mechanism of antimicrobial activity of chitosan films is based on the chemical interaction of positively charged amino groups (NH_3^+) in chitosan with the negatively charged groups of microbial surfaces (Butnaru *et al.*, 2019). This interaction can disturb the structural and functional integrity of microbial cell membranes leading to leakage of intracellular substances, ultimately causing microbial cell death (Yu *et al.*, 2022). This protects the products from microbial decay and leads to preserving the quality of the food products. Also, several other studies suggested that the application of chitosan-based films or coatings can develop a protective layer on the surface of the food material which acts as a barrier against external microbial attacks. Another possible mechanism of antimicrobial activity is based on the chelating properties of chitosan. Chitosan has the ability to chelate metal ions on bacterial surfaces which produces unusable forms of chelated complexes, consequently leading to inhibition of the microbial growth (Yu *et al.*, 2022).

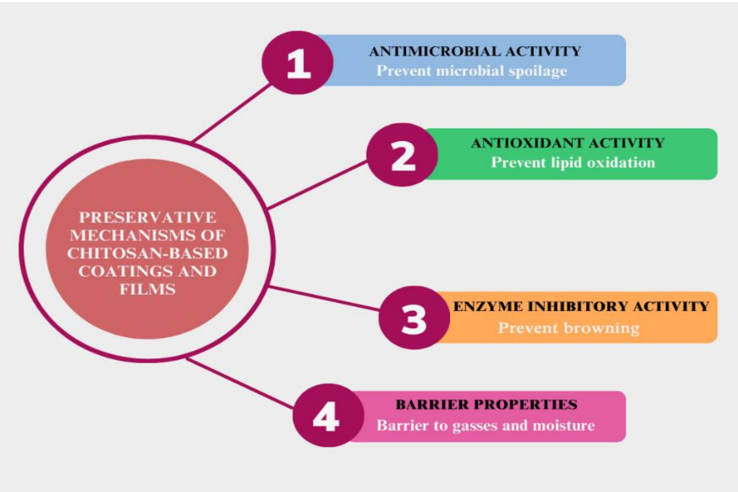

Figure 1: Preservative mechanisms of chitosan-based coatings and films

Currently, studies have demonstrated the successful application of bio-based chitosan films or coatings in the preservation of a diverse range of food products including fresh fruits, vegetables, and meat products (Yu *et al.*, 2022). In the fresh produce industry, chitosan biofilms have been successfully used to preserve the natural characteristics of highly perishable food commodities such as tomatoes, strawberries, apples, mangoes, and pears (Zárate-Moreno *et al.*, 2023). A study conducted to assess the applicability of chitosan coatings incorporated with olive oil residue extracts to improve the shelf-life stability of apple and strawberry fruits, exhibited antifungal and antibacterial activities against spoilage and pathogenic strains, particularly *Penicillium expansum* and *Rhizopus stolonifera* (Khalifa *et al.*, 2016). Furthermore, this study recommends the use of chitosan coatings incorporated with olive oil residue extracts as a novel and natural substitute to synthetic coatings to preserve the apple and strawberry quality. According to Zhang *et al.* (2017), chitosan and chitosan-TiO_2 composite films have exhibited efficient antimicrobial activity against bacteria, fungi, and moulds in red grapes. This study further emphasizes that red grapes could be preserved for 15 d with the application of pure chitosan membranes and 22 days with chitosan-TiO_2 composite films. A study conducted to evaluate the use of chitosan-based films for the preservation of feijoa fruits revealed that chitosan biofilms have significantly reduced the growth of bacteria and fungi in the fruits coated with chitosan films (Zárate-Moreno *et al.*, 2023). Previous studies have also shown that tomatoes treated with chitosan coatings were successfully protected from the attacks of *Penicillium spp., Aspergillus spp.*, *Rhizopus stolonifer*, and *Botrytis cinerea* (Duan *et al.*, 2019).

Meat is one of the most perishable commercial food products and its shelf life is affected by several factors including microbial growth, enzymatic activity, oxidation processes, and package type (Fernando *et al.*, 2024). Chitosan-based coatings and/or films have been used as a sustainable biopolymer to extend the shelf life of meat products in the meat industry. A study conducted to investigate the effect of chitosan coating and vacuum packaging on the microbiological and chemical properties of beef concluded that the application of chitosan coating in beef reduced the total mesophilic aerobic bacteria and lactic acid bacteria counts. Meanwhile, it completely inhibited the growth of *S. aureus* up to d 15 (Duran and Kahve, 2020). A study conducted by Liu *et al.* (2021), revealed that chitosan-based films incorporated with different spice extracts have a prominent inhibitory effect against *S. aureus* and *E. coli* in refrigerated pork. It further concluded that the shelf life of pork coated in composite chitosan films was prolonged up to 7 d.

Fish, another highly perishable food product, requires various preservation techniques to maintain its quality and extend shelf-life. Kakaei and Shahbazi (2016) examined the effect of chitosan-gelatin film incorporated with ethanolic red grape seed extract and *Ziziphora clinopodioides* essential oil on the survival of *L. monocytogenes* of minced trout fillet. According to this study, fish spoilage was significantly delayed in samples wrapped in chitosan-gelatin film containing grape seed extract and *Ziziphora clinopodioides* essential oil compared to the control samples.

Chitosan-based coating and films are considered promising techniques in food preservation due to their excellent properties, including antimicrobial properties, film-forming ability, the capacity to avoid moisture and aroma loss, impermeability to oxygen, non-toxicity, and safety (Broek *et al.*, 2015). The antimicrobial activity of chitosan is influenced by several factors, including its source, degree of polymerization, and environmental conditions, particularly the pH value (Thambiliyagodage *et al.*, 2023). Despite these influencing variables, chitosan as a natural and renewable biopolymer, presents a promising sustainable alternative to conventional plastic packaging materials, which are often associated with low biodegradability. Consequently, chitosan-based coatings and films offer a viable green solution not only for replacing traditional packaging but also as a sustainable alternative to conventional food preservation methods. (Butnaru *et al.*, 2019).

Algae as a preservative

The application of novel antimicrobial agents derived from natural resources has currently become a global concern of immense significance. Marine algae have recently been frosted as one of the most abundant, renewable, and unexposed sources of antimicrobial agents to replace chemical additives in the food industry (Surendhiran *et al.*, 2021). Algae are prokaryotic or eukaryotic photoautotrophic organisms characterized by their photosynthetic nature. Algae are classified into two major groups multicellular organisms known as macroalgae or seaweed, and unicellular organisms, known as microalgae (Babich *et al.*, 2022; Pina-Pérez *et al.*, 2017). Both macroalgae and microalgae are proven to be excellent sources of an array of biologically active secondary metabolites, that make them a house of remarkable antioxidant and antimicrobial properties (Kang *et al.*, 2013). With the rising consumer demand for natural, and functional food additives, the use of macroalgae and microalgae extracts with antibacterial and antifungal activity serves as a potential preservative in the food industry (Pina-Pérez *et al.*, 2017).

Sáez *et al.* (2021), examined the potential of *Crassiphycus corneus, Ulva ohnoi, Arthrospira platensis*, and *Haematococcus pluvialis* algae extracts on extending the shelf life of rainbow trout (*Oncorhynchus mykiss*) fillets. The study concluded that all algae extracts delayed the microbial growth and lipid oxidation in trout fillets during the cold storage period compared to the control while improving the textural parameters of trout fillets. A study conducted to assess the effect of the addition of seaweed extracts of *Fucus vesiculosus*, and *Bifurcaria bifurcata* algae species on the oxidative stability of refrigerated low-fat pork liver patties, revealed a higher lipid and protein stability accompanied by the treated samples compared to control samples (Agregán *et al.*, 2018). According to Feki *et al.* (2021), the incorporation of polysaccharides isolated from the red macro alga *Falkenbergia rufolanosa* in beef sausages showed a significant decrease in the microbial counts along with marked stability in the color parameters and textural properties during 12 days of storage.

A study conducted to investigate the effect of seaweed coatings of the red algae *Kappaphycus alvarezii* and the brown algae *Sargassum tenerrimum* on the quality characteristics and shelf life of tomatoes revealed that both algae coatings have promising antibacterial activity against a wide range of bacteria including *Bacillus subtilis, S. aureus, Lactobacillus acidophilius, E. coli, Pseudomonas aeruginosa*, and *Proteus mirabilis* (Banu *et al.*, 2020). This study further concluded that the application of seaweed gel as a coating can extend the shelf life of tomatoes. As of that, the study pinpoints seaweeds as promising natural preservatives for improving the shelf life of tomatoes and maintaining their quality. Egistha Putri *et al*. (2020) examined the effect of edible coating made from extracellular polymeric substances produced by microalgae *Chlorella spp*. on strawberry shelf life. According to this study, the application of 50% extracellular polymeric substances of *Chlorella spp*. could prolong the shelf-life of strawberry fruits and reach the decaying phase by day 10 in low temperatures. Another study conducted to assess the potential use of *Spirulina platensis* microalgae-derived organic nanodots as a preservative in litchi beverage revealed that the total bacterial and fungal counts found in the treated sample were less than the untreated samples and showed an enhanced shelf life along with better sensory attributes in litchi beverage (Pyne *et al.*, 2022).

Though marine algae serve as a sustainable and ‘greener’ alternative to synthetic preservatives in the food industry, the application of algae in food products is with the poor sensory quality accompanied by the residual flavour, aroma, and toxicological issues such as accumulation of arsenic, heavy metals, and contaminants (Bouga and Combet, 2015). According to Colonia *et al*. (2023), deodorization is a major method to overcome sensory quality-related issues in marine algae-incorporated foods. Deodorization leads to the removal of off-flavour and off-odour compounds formed from algal biomass, such as volatile compounds and free fatty acids. However, the number of studies and applications of algae as a preservative in real food matrices seems comparatively low and thus, it has opened up new opportunities in the research field with timely application at the industrial level (Pina-Pérez *et al.*, 2017).

CONCLUSION

The application of green technologies in food preservation has gained significant attention in recent years due to the increasing resource consumption of the food industry and its associated environmental impact. Concurrently, the growing consumer awareness regarding health impacts concomitant with synthetic food additives has further escalated the interest in greener alternatives. As a result, novel preservation technologies such as ozone-based preservation, encapsulated essential oils, curcumin-based photosensitization, chitosan-based coatings and films, and the use of algae as preservatives have been explored as greener, cleaner, and more efficient alternatives for conventional food preservation techniques. These technologies contribute to reduced energy consumption, lower harmful emissions, improved process efficiency, and enhanced product quality aligning well with the principles of sustainability, eco-friendliness, and economic feasibility. Despite their potential, the widespread applications of these green preservation strategies in real food matrices remain still limited with challenges such as high cost and technological complexities during commercial level implementation. This highlights a critical research opportunity to bridge the gaps between laboratory-scale innovations and real-time industrial-level implementations, thereby facilitating broad opportunities for adopting these green preservation technologies in the food industry. Developing cost-effective methods for integrating these technologies into diverse food products, optimizing their performance, and ensuring their scalability for industrial applications through research would help to thrive these green preservation technologies in future food sector.

REFERENCES

Afsah-Hejri, L., Hajeb, P. and Ehsani, R.J. (2020). Application of ozone for degradation of mycotoxins in food: A review. Comprehensive Reviews in Food Science and Food Safety. 19(4), 1777–1808.

Agregán, R., Franco, D., Carballo, J., Tomasevic, I., Barba, F.J., Gómez, B., Muchenje, V. and Lorenzo, J.M. (2018). Shelf life study of healthy pork liver pâté with added seaweed extracts from *Ascophyllum nodosum, Fucus vesiculosus* and *Bifurcaria bifurcata*. Food Research International. 112, 400–411.

Amighi, M., Zahedifar, M., Alizadeh, H. and Payandeh, M. (2023). Encapsulation of *Nepeta hormozganica* and *Nepeta dschuprensis* essential oils in shrimp chitosan NPs: Enhanced antifungal activity. International Journal of Biological Macromolecules. 238, 124112.

Amit, S.K., Uddin, M.M., Rahman, R., Islam, S.M.R. and Khan, M.S. (2017). A review on mechanisms and commercial aspects of food preservation and processing. Agriculture and Food Security. 6(1). 6–51.

Augusto, P.E.D., Soares, B.M.C. and Castanha, N. (2018). Conventional technologies of food preservation pp. 3-23. In: Francisco, J. B., De Souza, A., Vibeke, O. and Mohamed, K. (Ed.), Innovative technologies for food preservation: Inactivation of spoilage and pathogenic microorganisms. Academic Press, USA.

Ayranci, U.G., Ozunlu, O., Ergezer, H. and Karaca, H. (2020). Effects of ozone treatment on microbiological quality and physicochemical properties of turkey breast meat. Ozone: Science and Engineering. 42(1), 95–103.

Babich, O., Sukhikh, S., Larina, V., Kalashnikova, O., Kashirskikh, E., Prosekov, A., Noskova, S., Ivanova, S., Fendri, I., Smaoui, S., Abdelkafi, S., Michaud, P. and Dolganyuk, V. (2022). Algae: Study of edible and biologically active fractions, their properties and applications. Plants. 11(6), 780.

Banu, A.T., Ramani P,S. and Murugan, A. (2020). Effect of seaweed coating on quality characteristics and shelf life of tomato (*Lycopersicon esculentum mill*). Food Science and Human Wellness. 9(2), 176–183.

Botondi, R., Barone, M. and Grasso, C. (2021). A review into the effectiveness of ozone technology for improving the safety and preserving the quality of fresh-cut fruits and vegetables. Foods. 10(4), 748.

Bouga, M. and Combet, E. (2015). Emergence of seaweed and seaweed-containing foods in the UK: Focus on labeling, iodine content, toxicity and nutrition. Foods. 4(2), 240–253.

Brodowska, A.J., Nowak, A. and Śmigielski, K. (2018). Ozone in the food industry: Principles of ozone treatment, mechanisms of action, and applications: An overview. Critical Reviews in Food Science and Nutrition. 58(13), 2176–2201.

Butnaru, E., Stoleru, E., Brebu, M.A., Darie-Nita, R.N., Bargan, A. and Vasile, C. (2019). Chitosan-based bionanocomposite films prepared by emulsion technique for food preservation. Materials. 12(3), 373.

Colonia, B.S.O., De Melo Pereira, G.V., De Carvalho, J.C., Karp, S.G., Rodrigues, C., Soccol, V.T., Fanka, L.S. and Soccol, C.R. (2023). Deodorization of algae biomass to overcome off-flavors and odor issues for developing new food products: Innovations, trends, and applications. Food Chemistry Advances. 2, 100270.

Damyeh, M.S., Mereddy, R., Netzel, M E. and Sultanbawa, Y. (2019). Curcumin-based photosensitization: a novel and green technology to decontaminate food systems. Comprehensive Reviews in Food Science and Food Safety. 19(4), 1727–1759.

Dias, L.D., Blanco, K.C., Mfouo-Tynga, I.S., Inada, N.M. and Bagnato, V.S. (2020). Curcumin as a photosensitizer: From molecular structure to recent advances in antimicrobial photodynamic therapy. Journal of Photochemistry and Photobiology C: Photochemistry Reviews. 45, 100384.

Duan, C., Meng, X., Meng, J., Khan, M.I.H., Dai, L., Khan, A., An, X., Zhang, J., Huq, T. and Ni, Y. (2019). Chitosan as a preservative for fruits and vegetables: A review on chemistry and antimicrobial properties. Journal of Bioresources and Bioproducts. 4(1), 11–21.

Duran, A. and Kahve, H.I. (2020). The effect of chitosan coating and vacuum packaging on the microbiological and chemical properties of beef. Meat Science. 162, 107961.

Egistha Putri, R.A., Sri Winasti, N.M., Dharmawan, M.T.T. and Suyono, E.A. (2020). Concentrations differences of microalgal extracellular polymeric substances as edible coating in shelf-life extension of *Fragaria spp*. AIP Conference Proceedings. 2260(1), 9003.

Fan, X. (2021). Gaseous ozone to preserve quality and enhance microbial safety of fresh produce: Recent developments and research needs. Comprehensive Reviews in Food Science and Food Safety. 20(5), 4993–5014.

Feki, A., Sellem, I., Hamzaoui, A., Ben Amar, W., Mellouli, L., Zariat, A., Nasri, M. and Ben Amara, I. (2021). Effect of the incorporation of polysaccharide from *Falkenbergia rufolanosa* on beef sausages for quality and shelf life improvement. LWT: Food Science and Technology. 143, 111139.

Fernando, S.S., Jo, C., Mudannayake, D.C. and Jayasena, D.D. (2024). An overview of the potential application of chitosan in meat and meat products. Carbohydrate Polymers. 324, 121477.

Freitas-Silva, O., Coelho, Coelho, C.C.S., Trombete, F.M. and Souza, De Souza, A.M. (2024). Current development in ozone-based food preservation pp 235-258. In: Amit, K. J. and Shankar, S. (Ed.), Food Packaging and Preservation. Academic Press, USA.

Hasani, S., Ojagh, S.M., Ghorbani, M. and Hasani, M. (2020). Nano-encapsulation of lemon essential oil approach to reducing the oxidation process in fish burger during refrigerated storage. Journal of Food Biosciences and Technology. 10(1), 35–46.

Hasheminejad, N. and Khodaiyan, F. (2020). The effect of clove essential oil loaded chitosan nanoparticles on the shelf life and quality of pomegranate arils. Food Chemistry. 309, 125520.

Huang, J., Chen, B., Zeng, Q.H., Liu, Y., Liu, H., Zhao, Y. and Wang, J.J. (2021). Application of the curcumin-mediated photodynamic inactivation for preserving the storage quality of salmon contaminated with *L. monocytogenes*. Food Chemistry. 359, 129974.

Joardder, M.U.H. and Masud, M.H. (2019). Food preservation techniques in developing countries. First ed. Springer Cham, Switzerland.

Kakaei, S. and Shahbazi, Y. (2016). Effect of chitosan-gelatin film incorporated with ethanolic red grape seed extract and *Ziziphora clinopodioides* essential oil on survival of *Listeria monocytogenes* and chemical, microbial and sensory properties of minced trout fillet. LWT: Food Science and Technology. 72, 432–438.

Kang, M.C., Cha, S.H., Wijesinghe, W.A.J.P., Kang, S.M., Lee, S.H., Kim, E.A., Song, C.B. and Jeon, Y.J. (2013). Protective effect of marine algae phlorotannins against AAPH-induced oxidative stress in zebrafish embryo. Food Chemistry. 138(2–3), 950–955.

Khalifa, I., Barakat, H., El-Mansy, H.A. and Soliman, S.A. (2016). Improving the shelf-life stability of apple and strawberry fruits applying chitosan-incorporated olive oil processing residues coating. Food Packaging and Shelf Life. 9, 10–19.

Khanashyam, A.C., Shanker, M.A., Kothakota, A., Mahanti, N.K. and Pandiselvam, R. (2022). Ozone applications in milk and meat industry. Ozone: Science and Engineering. 44(1), 50–65.

Knorr, D. and Augustin, M.A. (2023). Preserving the food preservation legacy. Critical Reviews in Food Science and Nutrition. 63(28), 9519–9538.

Pawar, K.R., Atkari, V.T., Pawar, D.A. and Ukey, P.D. (2021). Ozone treatment: The green technology in food industry pp. 11–22. In: A. K. Hagdar, A. K. Shinde, and A. H. Sayyed (Ed.), Green perspectives in food processing. NIPA GenX Electronic Resources and Solutions Pvt. Ltd., New Delhi.

Liao, W., Badri, W., Dumas, E., Ghnimi, S., Elaissari, A., Saurel, R. and Gharsallaoui, A. (2021). Nanoencapsulation of essential oils as natural food antimicrobial agents: An overview. Applied Sciences. 11(13), 5778.

Lin, Y., Hu, J., Li, S., Hamzah, S.S., Jiang, H., Zhou, A., Zeng, S. and Lin, S. (2019). Curcumin-based photodynamic sterilization for preservation of fresh-cut hami melon. Molecules. 24(13), 2374.

Liu, F., Li, Z., Cao, B., Wu, J., Wang, Y., Xue, Y., Xu, J., Xue, C. and Tang, Q.J. (2016). The effect of a novel photodynamic activation method mediated by curcumin on oyster shelf life and quality. Food Research International. 87, 204–210.

Liu, T., Liu, L., Gong, X., Chi, F. and Ma, Z. (2021). Fabrication and comparison of active films from chitosan incorporating different spice extracts for shelf life extension of refrigerated pork. LWT: Food Science and Technology. 135, 110181.

Macías-Cortés, E., Gallegos-Infante, J. A., Rocha-Guzmán, N. E., Moreno-Jiménez, M. R., Medina-Torres, L. and González-Laredo, R. F. (2020). Microencapsulation of phenolic compounds: Technologies and novel polymers. Revista Mexicana de Ingeniera Quimica. 19(2), 491–521.

Mukubesa, N., Nguenha, R., Hong, H.T., Seididamyeh, M., Netzel, M.E. and Sultanbawa, Y. (2022). Curcumin-based photosensitization, a green treatment in inactivating *Aspergillus flavus* spores in peanuts. Foods. 11(3), 354.

Munasinghe, M.A.J.P., Alwis, H., Bandara, R.M.A.S. and Weerakkody, G. (2022). Impact of cardamom, cinnamon and ginger essences on keeping quality of butter. Journal of Agriculture and Value Addition. 5(1), 107–114.

Munir, Z., Banche, G., Cavallo, L., Mandras, N., Roana, J., Pertusio, R., Ficiarà, E., Cavalli, R. and Guiot, C. (2022). Exploitation of the antibacterial properties of photoactivated curcumin as 'green' tool for food preservation. International Journal of Molecular Sciences. 23(5), 2600.

Muñoz-Tebar, N., Pérez-Álvarez, J.A., Fernández-López, J. and Viuda-Martos, M. (2023). Chitosan edible films and coatings with added bioactive compounds: Antibacterial and antioxidant properties and their application to food products: A review. Polymers. 15(2), 396.

Ogwu, M.C., Sylvester, C.I. and Ntuli, N.R. (2024). Food safety and quality in the global south. First ed. Springer Nature. Singapore.

Ojeda-Piedra, S.A., Zambrano-Zaragoza, M.L., González-Reza, R.M., García-Betanzos, C.I., Real-Sandoval, S.A., and Quintanar-Guerrero, D. (2022). Nano-encapsulated essential oils as a preservation strategy for meat and meat products storage. Molecules. 27(23), 8187.

Olabiran, T.E., Awolu, O.O. and Ayo-Omogie, H.N. (2023). Quality chracterization of functional soy-based yoghurt incorporated with scent leaf (*Ocimum gratissimum*) essential oil microcapsules. Food Chemistry Advances. 3, 100336.

Pandiselvam, R., Subhashini, S., Banuu Priya, E.P., Kothakota, A., Ramesh, S.V. and Shahir, S. (2019). Ozone based food preservation: a promising green technology for enhanced food safety. Ozone: Science and Engineering. 41(1), 17–34.

Pandiselvam, R., Sunoj, S., Manikantan, M.R., Kothakota, A. and Hebbar, K.B. (2017). Application and Kinetics of Ozone in Food Preservation. Ozone: Science and Engineering 39(2). 115–126.

Pina-Pérez, M.C., Rivas, A., Martínez, A. and Rodrigo, D. (2017). Antimicrobial potential of macro and microalgae against pathogenic and spoilage microorganisms in food. Food Chemistry. 235, 34–44.

Prakash, A., Baskaran, R., Paramasivam, N. and Vadivel, V. (2018). Essential oil based nanoemulsions to improve the microbial quality of minimally processed fruits and vegetables: A review. Food Research International. 111, 509–523.

Pyne, S., Paria, K., Mandal, S.M., Srivastav, P.P., Bhattacharjee, P. and Barik, T.K. (2022). Green microalgae derived organic nanodots used as food preservative. Current Research in Green and Sustainable Chemistry. 5, 100276.

Reis, D.R., Ambrosi, A. and Luccio, M.D. (2022). Encapsulated essential oils: A perspective in food preservation. Future Foods. 5, 100126.

Rice, R.G. and Graham, D.M. (2001). U.S. FDA regulatory approval of ozone as an antimicrobial agent-What is allowed and what needs to be understood. Ozone News. 29(5), 1005962.

Sáez, M.I., Suárez, M.D., Alarcón, F.J. and Martínez, T.F. (2021). Assessing the potential of algae extracts for extending the shelf life of rainbow trout (*Oncorhynchus mykiss*) fillets. Foods. 10(5), 910.

Sarron, E., Gadonna-Widehem, P. and Aussenac, T. (2021). Ozone treatments for preserving fresh vegetables quality: A critical review. Foods, 10(3), 605.

Seidi Damyeh, M., Mereddy, R., Netzel, M.E. and Sultanbawa, Y. (2020). An insight into curcumin-based photosensitization as a promising and green food preservation technology. Comprehensive Reviews in Food Science and Food Safety. 19(4), 1727–1759.

Shajil, S., Mary, A. and Rani Juneius, C.E. (2018). Recent food preservation techniques employed in the food industry. Microbial Biotechnology. 2, 3–21.

Lone, S.A., Raghunathan, S., Davoodbasha, M.A., Srinivasan, H. and Lee, S.Y. (2019). An investigation on the sterilization of berry fruit using ozone: An option to preservation and long-term storage. Biocatalysis and Agricultural Biotechnology. 20, 101212.

Surendhiran, D., Li, C., Cui, H. and Lin, L. (2021). Marine algae as efficacious bioresources housing antimicrobial compounds for preserving foods: A review. International Journal of Food Microbiology. 358, 109416.

Taheri, A., Behnamian, M., Dezhsetan, S. and Karimirad, R. (2020). Shelf life extension of bell pepper by application of chitosan nanoparticles containing *Heracleum persicum* fruit essential oil. Postharvest Biology and Technology. 170, 111313.

Tao, R., Zhang, F., Tang, Q.J, Xu, C.S, Ni, Z.J. and Meng, X.H. (2019). Effects of curcumin-based photodynamic treatment on the storage quality of fresh-cut apples. Food Chemistry. 274, 415–421.

Thambiliyagodage, C., Jayanetti, M., Mendis, A., Ekanayake, G., Liyanaarachchi, H. and Vigneswaran, S. (2023). Recent advances in chitosan-based applications: A review. Materials. 16(5), 2073.

United Nations (2023). Peace, dignity and equality on a healthy planet (online). (Accessed on 17.04.2024). Available at: https://www.un.org/en/global-issues/food

Van Den Broek, L.A.M., Knoop, R.J.I., Kappen, F.H.J. and Boeriu, C.G. (2015). Chitosan films and blends for packaging material. Carbohydrate Polymers. 116, 237–242.

Vashisht, P., Verma, D., Singh, L., Saini, G.S., Sharma, S., Charles, A.P.R., Mahanta, S., Mahanta, S., Singh, K., Gaurav, G. and Kaur, J. (2024). Ozone processing of milk and milk products: A review of applications, quality effect and implementation challenges. International Journal of Food Engineering. 20(9-10), 669–680.

Viacava, G.E., Ayala-Zavala, J.F., González-Aguilar, G.A. and Ansorena, M.R. (2018). Effect of free and microencapsulated thyme essential oil on quality attributes of minimally processed lettuce. Postharvest Biology and Technology. 145, 125–133.

Ummat, V., Singh, A.K. and Sidhu, G.K. (2018). Effect of aqueous ozone on quality and shelf life of shredded green bell pepper (*Capsicum annuum*). Journal of Food Processing and Preservation. 42(10), 1–14.

Xue, W., Macleod, J. and Blaxland, J. (2023). The use of ozone technology to control microorganism growth, enhance food safety and extend shelf life: A promising food decontamination technology. Foods. 12(4), 814.

Yang, T., Qin, W., Zhang, Q., Luo, J., Lin, D. and Chen, H. (2023). Essential-oil capsule preparation and its application in food preservation: A review. Food Reviews International. 39(7), 4124–4158.

Yu, D., Yu, Z., Zhao, W., Regenstein, J.M. and Xia, W. (2022). Advances in the application of chitosan as a sustainable bioactive material in food preservation. Critical Reviews in Food Science and Nutrition. 62(14), 3782–3797.

Yu, X., Zou, Y., Zhang, Z., Wei, T., Ye, Z., Yuk, H.G. and Zheng, Q. (2022). Recent advances in antimicrobial applications of curcumin-mediated photodynamic inactivation in foods. Food Control. 138, 108986.

Zárate-Moreno, J.C., Escobar-Sierra, D.M. and Ríos-Estepa, R. (2023). Development and evaluation of chitosan-based food coatings for exotic fruit preservation. BioTech. 12(1), 20.

Zhang, L., Zhao, S., Cui, L. and Wu, L. (2020). Exploring green innovation practices: Content analysis of the fortune global 500 companies. SAGE Open. 10(1), 1–13.

Zhang, W., Ezati, P., Khan, A., Assadpour, E., Rhim, J. W. and Jafari, S.M. (2023). Encapsulation and delivery systems of cinnamon essential oil for food preservation applications. Advances in Colloid and Interface Science. 318, 102965.

Zhang, X., Xiao, G., Wang, Y., Zhao, Y., Su, H. and Tan, T. (2017). Preparation of chitosan-TiO_2 composite film with efficient antimicrobial activities under visible light for food packaging applications. Carbohydrate Polymers. 169, 101–107.

Zhang, Z., Zhang, S., Su, R., Xiong, D., Feng, W. and Chen, J. (2019). Controlled release mechanism and antibacterial effect of layer-by-layer self-assembly thyme oil microcapsule. Journal of Food Science. 84(6), 1427–1438.

Zou, Y., Yu, Y., Cheng, L., Li, L., Zou, B., Wu, J., Zhou, W., Li, J. and Xu, Y. (2021). Effects of curcumin-based photodynamic treatment on quality attributes of fresh-cut pineapple. LWT: Food Science and Technology. 141, 110902.