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Ozone applications: from farm to fork and from A to Z

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Summary

Ozone is a strong oxidant and can be generated easily by simple machinery. In addition to its potent functions on microbial control, through innovative ideas and applied in better modes and doses, it can be used within our daily activities, and for a healthier life. This article summarizes novel applications of ozone in food science, from farm to fork levels (primary production, trading, transportation, retail, commercial and domestic processing), and compiled from A to Z for easier keyword search.

Riassunto

L'ozono è un forte ossidante e può essere facilmente generato con semplici strumenti. In aggiunta alle sue potenti funzioni sul controllo microbico, attraverso idee innovative e applicate in migliori modalità e dosi, può essere utilizzato nelle nostre attività quotidiana, e per una vita più sana. Questo articolo riassume le nuove applicazioni dell'ozono nella scienza dell'alimentazione, dalla fattoria ai vari livelli della tavola (produzione primaria, commercio, trasporto, vendita al dettaglio, trasformazione, lavorazione commerciale e domestica), ed è organizzato in ordine alfabetico dalla A alla Z per una più facile ricerca delle parole chiave.

Introduction

Ozone is a strong oxidant and potent disinfecting agent. It has had industrial applications for over 100 years, mostly in European countries. In 1982 the United States Food and Drug Administration (FDA) granted "generally recognized as safe" (GRAS) status for use of ozone in bottled water. In 1997, it was decreed that ozone is a GRAS substance for use as a disinfectant or sanitizer for foods when used in accordance with good manufacturing practices (GMPs). Since these milestones of acceptance, and other factors, including advancement in voltage control, there were rapid developments on ozone application. For example, ozone applications in the food industry and catering are accepted for surface hygiene, sanitation of plant equipment, reuse of waste water, treatment and lowering biological oxygen demand and chemical oxygen demand of food waste (1). This article attempts to summarize major ozone applications in food supply logistics with a wider scope, from farm to fork levels (primary production, trading, transport, retail, commercial and domestic processing), and compiled from A to Z for easy keyword search.

Agriculture

Pre-harvest

The importance of ozone applications in agriculture can be partially read in the report submitted to the California Energy Commission in 1999 (2); including the roles of ozone in soil fumigation, aqueous disinfectant, gas fumigant, fruit storage and wastewater management. The effects of ozone to soil are complicated, as soil matrix is heterogeneous. Johnson and Pregitzer (3), after site investigation, suggested that the concentration of soluble phenolic acids and free amino acids in soil were strongly influenced by soil properties, plant and microbial activity, plant community and to a lesser degree, changes in atmospheric O3. McCrady & Andersen (4) reported that rhizosphere microbial activity may be initially stimulated by plant exposure to ozone. Elevated ozone in rhizosphere may influence the dynamic of decomposition processes and the turnover of nutrients (5).

There are numerous reports indicating the adverse impacts of ozone in agriculture, e.g. to rice (6) and cotton (7). Pasqualini et al. (8) reported that atmospheric ozone decreased the gallic acid and vanillin levels in Aleppo pine. In 2000, ozone induced global yield reduction ranged 8.5-14% for soybean, 3.9-15% for wheat and 2.2-5.5% for maize (9), with ozone as an air pollution index. Different models for mapping potential ozone damage on vegetation showed very different spatial variations in the risk (10) and the role of ozone by itself may be quite different (see Section Antioxidant).

Post-harvest

Ozone, in the form of gas and ozonated water, is getting more popularly used for the preparation of fresh cut vegetables. Ozone treatment was found to be better than the chlorine and organic acid treatments in maintaining the sensory quality of lettuce (11). It is expected that an excessive dose of oxidants will consume the antioxidant in mature fruits where the pericarp is already well developed. However, contact of ozone with fruit juice should be avoided as it will greatly hit anthocyanins, ascorbic acid and color values (12).

Antioxidant production

Reactive oxygen species (ROS) are an unenviable part of aerobic life. The dynamic equilibrium in vascular plants can be disturbed leading to enhanced ROS level and damage to cellular constituents which is called oxidative stress (13). However, in recent years, research in biology showed special interest in ROS on enhancing plant tolerance.

Ozone can be used as an oxidative stress to induce the production of antioxidants in fruits or vegetables; other factors include temperature, UV exposure and pathogenic attacks (14). The effect of ozone treatment on total phenol, flavonoid, and vitamin C content of fresh-cut honey pineapple, banana and guava was investigated by Alothman et al. (15). The antioxidant capacity of the fruits was evaluated by measuring the ferric reducing/antioxidant power (FRAP) and 1,1-diphenyl-2-picrylhydrazyl (DPPH). Total phenol and flavonoid contents of pineapple and banana increased significantly after exposure to ozone for up to 20 min, with a concomitant increase in FRAP and DPPH values; however, the opposite was observed for guava. Ascorbic acid (AS) increase is used as a systemic response to ozone stress; in the study conducted by Severino et al. (16), ozone-resistant clones of *Trifolium repens* and *Centaurea jacea* showed the highest concentration of antioxidants, with 50-70% more AS than ozone-sensitive clones. Liu et al. (17) also reported that antioxidant and total phenolic content were affected by environmental conditions. Elevated ozone increased the net photosynthetic rate of red clover leaves and antioxidant phenolic compounds before visible injuries in a large area study (18). In sunflower, reduced plasticity of cell wall induced by ozone exposure may oppose an unspecific mechanical resistance against abiotic stress (19).

Increases in antioxidant level in crops may be good for consumers but not be favorable for farmers. Frei et al. (6) studied the effects of ozone exposure on feeding quality of rice shoots for ruminant herbivores. Rice biomass was reduced by an average of 24% and significant reduction was observed in crude protein content after ozone treatment; however, the antinutritive lignin and phenolic components increased.

Aquaculture

In 1970, fish from aquaculture that was consumed by human was 0.7 kg per capital. This value rose dramatically to 7.8 kg per capital in 2008 (20). China is the largest country producing fish products with 47.5 million tonnes in 2008. Since the same year, fish products in China from aquaculture (68.8%) overshot the figure of capturing from natural water bodies. For aquaculture in Europe, recirculating aquaculture systems (RAS) provide opportunities to reduce water usage and to improve waste management and nutrient recycling. Ozone is helpful for RASs especially on nitrogen budget control and sludge thickening (21). It had been considered that ozone-produced oxidants (OPO) during ozonation of seawater may lead to toxicity impacts. If excessive ozone is applied in water, it will affect the physiological activities and mucus function of fish. However, it only occurred on fish samples after the ORP was increased to an extremely high level of 600 mV (Fong et al., 2011). Reiser et al. (22) using 0.06 mg/l and above OPO for a 21-day study reported that no major alterations in histological and physiological parameters were observed in juvenile turbot. Similar safe levels were reported by Schrader et al. (23) on Pacific white shrimp.

Biosecurity

Food safety, from farm to fork, and human health implications were well noted (24). On a larger scope, biosecurity for the worker and organism in food supply chains, environment and consumer is of equal important. Ozone alone or in combination with UV can effectively disinfect recirculating water before it returns to the fish culture tank (25). This application is especially important in live seafood logistics and temporarily holding at Chinese restaurant aquarium tanks where fish density may be extremely high.

Bleach vs. ozone

Bleach and other oxidizers are getting more popular and used in the food industry and domestic environments. However, ozone is regarded as an environmentally friendly disinfectant as it rapidly disintegrates into water and oxygen. On the other hand, it has to be made on site because of its instability and may react and disintegrate before reaching the target organism (26).

Color

Do not expose foods to ozone, unless you want to see its faded glory. Ozone is very effective for color removal, including natural and artificial colors (27). In an early article published in 1907, Bridge has already indicated that ozone discharges vegetable colors (28).

Depuration

Ozone is suited for depuration of contaminated seafood. It was reported that ozonated water treatment reduced the total microbial load of fresh Pacific oysters by about 10-fold (29). In another study, southern quahog clams (*Mercenaria campechiensis*) were dosed with *Vibrio vulnificus* and placed in a pilot-scale depuration system using ozonated recirculated artificial seawater. Twenty-four hours of treatment with ozone-treated recirculating artificial seawater reduced the numbers of *V. vulnificus* in the shellfish meats by an average of 2 log units when compared to natural die-off in control clams (30). Application of ozone for depuration of seafood is also effective for Florida red tide organisms and its associated toxins removal (31).

Environmental Friendly; Egg

Excessive ozone will be depleted by itself and leaving not problem of residual effects compared to other forms of chemicals for food treatment. For example, after cleansing of poultry egg, the shelf life can be extended. However, it also imposes a controversial issue of life cycle assessments of long-distance transportation of foods (32).

Flotation separation

While air aeration does not, ozone produced effective solid-liquid separation through flotation (33), which is helpful especially for treatment of catering waste with high levels of protein fragments and grease.

Gas

Ozone at ordinary temperature and atmospheric conditions is a gas. Except under laboratory conditions, all ozone produced for industrial or domestic use is generated by coronary discharge method or by UV. Dissolving ozone into water produces ozonated water. Oxygen level in ambient gas is relatively low (20.9%); as a general rule, it is impossible to feed ambient air into an ozone generator so as to produce ozonated water with dissolved ozone above 10 mg/L. If higher concentration of ozone gas and ozonated water is to be produced, high concentration of oxygen, supplied from an oxygen cylinder or by molecular sieve oxygen generation, must be employed.

Hydroponic culture

Disease control is difficult in mass hydroponic culture, as the pathogens may be reinoculated in the recirculation process (34). In addition to chemical control, other methods in disease control in hydroponic systems include ozone, UV, filtration, adsorption and biological control (35).

Indoor Air quality, work place

Ozone is one of the parameters for indoor air quality objective. It is also an index for outdoor air quality as a secondary pollutant. It is getting more popular to use ozone for indoor microbial control, especially for pharmaceutical and food production. Guidelines and recommendation for safe use of ozone were summarized by Rosenthal (36).

Juvenile fish culture

Ozone is mostly effective in continuous water disinfection process for recirculating aquaculture systems (37), which is very important for juvenile fish culture. Ozone systems are also cost-effective and carry low risk in biosecurity control in fingerling husbandry (38).

Kitchen

Pesticide application should be

avoided in kitchens to prevent accidental food poisoning, especially with rodenticides. However, not many people realize that if ozone is applied in a kitchen at very low dose, it will remove the odor or ordinary pests including rats, cockroaches and ants. Pheromones and odor from droppings are important gas messages telling common kitchen pests that it is their city hall and meeting point. Ozone is effective to remove odors and pheromones. Kitchen pests will not feel at home without the odor they are used to; then, they will leave the kitchen, and seek for another more "comfortable" place.

Laundry

Table cloth washing demands a huge quantity of water. Apart from hospital soiled fabric, high temperature disinfection is not necessary for washing ordinary fibers, including table cloths and napkins. Ozonated water laundry is effective to remove difficult stains in soiled fibers. Ozone will also remove the odor in fiber; no restaurant customers would like to put on a napkin with a special smell!

Microbial control

Ozone is effective on microbial control for postharvest pathogenic fungi or commodities that tolerate this gas, such as *Penicillium* and *Botrytis* species on grapes (39). Factors affecting antimicrobial effects on food including 1) form of application (gaseous or dissolved), 2) ozone concentration (40), 3) microbial densities, 4) temperature, 5) pH, 6) contact time, 7) physiological status of the organisms (actively growing parts are more susceptible than spores) and 8) physicochemical properties of the outermost layer of organisms, 9) present of protective layer (e.g. whipping cream) in food (41).

Nitrite

Similar to carbon monoxide to humans, nitrite is toxic to aquatic life. Nitrite combines with hemoglobin and forms methemoglobin. Nitrite levels should be kept below 0.1 mg/L to avoid fish death (42). Ozone is mostly effective in nitrite removal, when compared to other forms of nitrogen compounds in aquaculture (43).

Odor and taste control

Ozone is effective for odor control of kitchen waste gas. In aquaculture, however, unless at a high dose with resultant oxidation reduction potential (ORP) higher than 600 mV, ozonation will not affect the fish mucus density and activity (44). Ozone also will not affect the "earthy" and "musty" off-flavors in fish culture due to the presence of metabolites geosmin and 2-methylioboreol (MIB) (45).

Pharmaceutical production and packaging

Ozone is commonly employed for indoor air quality control for pharmaceutical production and packaging to avoid air-borne pathogen contamination. Similarly, ozone systems are also suitable for air quality control of food processing units.

Quickly disappears after application, no secondary pollutant will be left; it is an advantage of ozone application. However, no long-lasting effect is also a disadvantage of ozone use.

Removal of pesticide residues

Ozonated water was effective for pesticide removal [fenitrothion: (46); diazinon, parathion, methyl-parathion, cypermethrin] (47). After ozonation, the tested pesticide by-products did not cause adverse effects on gap junctional intercellular communication in cell lines and therefore was considered safe (48). The major constraint is the availability of machinery for production of ozonated water, with high level of dissolved ozone for commercial and domestic use. Low cost machinery for production of microbubble with dissolved ozone should be available in the market in the near future; rinsing water with ozone microbubble is most effective for pesticide removal (49).

Shelf life and sterilization

Ozone treatment delayed both the development of red color, as well as rotting in tomato, and shelf life was enhanced by 12 days at 15°C (50). Continuous low ozone exposure (50 nL/L) was effective for decay control caused by *Sclerotinia sclerotiorum* and *Botrytis cinerea* and extended the storage period up to 6 months (51). Tzortzakis et al. (52) reported that ozone-enrichment maintained tomato fruit firmness and did not affect fruit weight.

Toxicity

Ozone is commonly considered toxic and it is bad to have excessive level in the troposphere. The controversial clinical issue of ozone, especially on the damages on respiratory system and extrapulmonary organs was discussed by Bocci (53) in his article "It it true that ozone is always toxic? The end of a dogma". Benefiting from the advancement in ozone sensing device, monitoring of ozone is relatively simple nowadays, and therefore it is quite safe for the food industry to employ ozone for food and environmental hygiene control.

Unstable

Ozone is unstable, and must be freshly prepared at the site of operation. However, it can be considered as one of the major superior features of ozone, as it will be gone by itself without leaving residues in the work place.

Virus deactivation; Veterinary

Ozone can chemically destroy the worst virus. It is effective for surface disinfection of haddock eggs against piscine nodavirus (54). It can inactivate norovirus in conditions relevant to healthcare (55). However, its efficacy on norovirus control on depuration of contaminated seafood is still uncertain, due to the complicated interaction between the virus and the host.

Water and wastewater treatment

Casani and Knøchel (56) compared water treatment methods for microbial decontamination of processed water in the food industry. The superior features for ozone included short contact time, sensitivity to turbidity and effects on microorganisms. The inferior features included high occupational hazards, corrosion and relatively high cost. Ozone is mostly effective for treatment of commercial aquaculture effluents (57). It is especially effective for phenolics removal in food wastewaters (58; 59). Synergistic effects are commonly observed for waste water treatment using ozone in combination with other oxidants such as hydrogen peroxide and UV radiation (60). However, some of the reported cases were of bench scale and employed excessive dose of ozone for optimal treatability - which causes a false impression to the reader that treatment may incur extensive energy cost. Actually, treatment will low concentration of ozone together with related technology (see flotation separation section) may also easily achieve superior outcomes.

Xenobiotic degradation

Ozone is suitable for the degradation of difficult xenobiotic compounds in food waste (61).

Yield

The ultimate concern for farmer, fishermen and food industry is on the yield and profit. There are numerous scientific articles describing the adverse effects on air pollution, and atmospheric ozone on crop yield (62). Therefore, ozone pollution poses a growing threat to global food security in the coming decades (63). Indeed high levels of ozone in air reduce plant growth, photosynthesis and carbohydrate allocation (7). Unfortunately, ozone is commonly used as an air pollution index for the overall quality of ambient air. However there is uncertainty on crop yield reduction purely caused by ozone -or other active air pollutants; further research is needed.

Zoonoses control

Zooplanktons are minute simple organisms; however, they are mostly opportunistic. They know how to survive and may have suitable biological function at suitable times and locations. The pros and cons effects of ozone in food industrial environments were summarized above. Ozone applicants should learn from zooplanktons; let ozone be applied at the right dose and right mode. Excessive levels should be avoided, as it wastes energy, may reduce the nutritional value and incurs inferior results.

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