APPLICATION OF OZONE TREATMENT IN AGRICULTURE AND FOOD INDUSTRY. A REVIEW
/
臭氧杀菌技术在农业和食品行业中的应用：综述

Ying WANG[1,2]; Xiao Jun QIAO*[1)]; ZhiBin WANG[1)]

[1)] Information Technology Research Center, Beijing Academy of Agriculture and Forestry Sciences, Beijing/ China;
[2)] Nongxin Technology (Beijing) Co., LTD
Tel: +86 01051503650; E-mail: qiaoxj@nercita.org.cn

DOI: https://doi.org/10.35633/inmateh-68-86

Keywords: *Ozone sterilization, Agriculture, Disease, Insect pest, Food industry, Plant protection technology*

ABSTRACT
Ozone is a strong oxidant and strong disinfectant that has a strong anti-pathogenic effect on bacteria, fungi, parasites, and viruses. Because of its advantages such as high reactivity, strong permeability and low residue, the application of ozone is gaining more and more attention, and ozone has been widely used in water treatment, equipment disinfection, public scene disinfection, and other fields. The purpose of this review is to discuss the use of ozone technology for animal and plant protection that can be applied to agriculture, and to emphasize the need for further studies to determine the optimal concentration and application of ozone for different crops so that, in the future, ozone technology can be applied in agriculture to gain a significant competitive advantage and improve product safety.

摘要
臭氧是一种强氧化剂和强消毒剂，对细菌、真菌、寄生虫和病毒有很强的抗病原作用。 由于臭氧具有反应活性高、渗透性强、残留量低等优点，其应用越来越受到重视，臭氧目前已广泛应用于水处理、设备消毒、公共场所消毒等领域。本综述的目的是讨论可应用于农业的臭氧技术在动植物保护中的应用，并强调需要进一步研究以确定不同作物的最佳臭氧浓度和应用，以便在未来在农业中，应用臭氧技术可获得显着的竞争优势，同时提高产品安全性。

INTRODUCTION
Ozone (O_3), an allotropic form of oxygen (O_2), is an unstable colorless gas with a unique smell. Ozone in the atmosphere is usually generated from atmospheric air that has been exposed to a high-energy source, such as ultraviolet radiation or high voltage electrical discharge. Ozone is partially soluble in water and its solubility increases when the partial pressure of the gas increases and the temperature of water decreases. It is an attractive alternative to insecticides and disinfectants because it auto decomposes into oxygen leaving no toxic residues in the environment (*Tiwari et al., 2008*).

The increasing importance of preventing and controlling plant diseases and insect pests in modern agriculture has led to the use of large amounts of insecticides and sterilizing agents to reduce the losses caused by crop diseases and pests. However, chemical pesticides are harmful to the environment and human health, and pesticides are single-targeted to crops, which can cause damage to other crops. Furthermore, the extensive use of chlorine-containing disinfectants in animal husbandry can cause residual problems and may spread harmful microorganisms to humans. In recent years, the focus has shifted more towards economically, environmentally, and socially sustainable development. In agriculture, there is a growing need to find and use methods that are safe for crops and have no adverse impacts on the environment, animals, or humans.

Ozone is an effective bactericide, insecticide, and fungicide that has the advantages of safety, efficiency, and environmental protection. Moreover, ozone can destroy up to 99.9% of pesticide residues and microorganisms commonly found on food because of its potential oxidizing capacity. As an oxidizing agent in organic reactions, ozone is used in many fields, including pulp bleaching, cooling water treatment, and disinfection of medical appliances *(Pandiselvam et al., 2017*). For many years, ozonation technology has been used in Europe to disinfect drinking water and swimming pool water without any problems (*Roustan M, 2008*).

---
[1] *Ying Wang, M.S.; XiaoJun Qiao, Prof. Ph.D.; ZhiBin Wang, Ph.D.*

In this review, the applications of ozone in agriculture were discussed, with particular attention to experiments and studies that have been reported in scientific papers, and analyze the advantages and constraints of using ozone technology in agriculture. This overview will provide guidelines for further research, the development of new ozone plant protection machinery, and the expansion of its applications in agricultural production.

PRODUCTION OF OZONE

Ozone is very unstable and breaks down quickly into oxygen at room temperature (Figure 1) *(Guzel-Seydim et al., 2004*), so it must be manufactured on site for immediate use (*Brodowska et al., 2018*). Common methods of ozone generation include electrolysis, reaction of elemental phosphorus with water, and radiochemical production. Considering the cost, the most popular methods now are photochemical (ultraviolet light) and corona discharge.

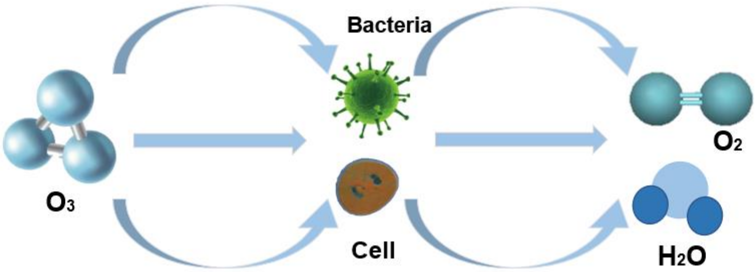

Fig.1 - Action of ozone on cells

Corona (Electrical) discharge method

Corona discharge involves passing dried dust-free air or another oxygen-containing gas mixture through a high-energy electrical field between two electrodes separated by a dielectric material, usually glass. When oxygen passes through the electrical field, the molecules are split apart, forming very active atomic oxygen radicals that can combine with intact oxygen molecules to produce ozone, as shown in the following equations.

An oxygen molecule (O_2) absorbs an electron (e^-) and splits into two oxygen atoms ($2O$).

$$O_2 + e^- \rightarrow 2O \tag{1}$$

Then, each oxygen atom (O) interacts with an oxygen molecule to produce ozone (O_3).

$$2O + 2O_2 \rightarrow 2O_3 \tag{2}$$

The mixture of ozone and gas discharged from an ozone generator contains approximately 1%–3% ozone if dry air is used, and 3%–6% ozone when high-purity oxygen is used as the feed gas (*Patil et al., 2011*).

The corona discharge method has been used widely to produce large amounts of ozone (Figure 2).

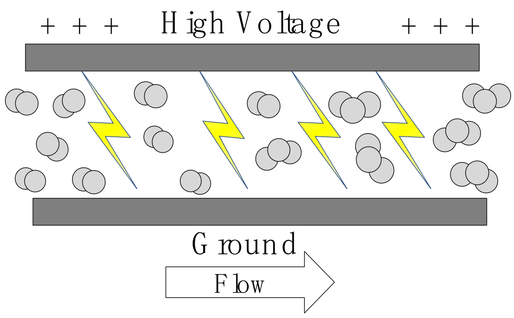

Fig. 2 - Schematic diagram of ozone generation by corona discharge (*Gonçalves, 2009*).

Ultraviolet lamp method

The ozone layer in the Earth's stratosphere is produced by ultraviolet radiation. Therefore, any ultraviolet light with wavelength <200 nm can dissociate oxygen molecules into oxygen atoms and produce ozone. Generally, an ultraviolet lamp with wavelength 140–190 nm can be used to split the oxygen molecules into unstable oxygen radical atoms (photodissociation), thereby starting the process of ozone production, as shown in equations (1) and (2).

The ultraviolet light from the lamp will convert the passing oxygen molecules to ozone (Figure 3). However, the efficiency of this method in generating ozone is very low, so it is best used when only a small amount of ozone is required.

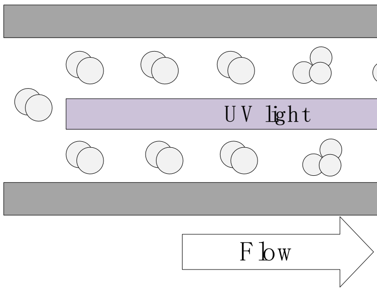

Fig. 3 - Schematic diagram of ozone generation by ultraviolet light (*Gonçalves, 2009*)

The main methods used for ozone generation are described in Table 1.

Table 1

Main methods used to generate ozone (*Cameron, 2012*)

Method	Basis	Advantage	Disadvantage
Corona discharge technology	High voltage; Gas	Fast response; Sufficient materials	High cost; Low ozone concentration; Large noise and electromagnetic interference
Ultraviolet lamp method	UV lamp; Gas	Lower cost; Output hardly affected by humidity	Low efficiency;
Electrochemical Ozone Production	Low voltage direct current	High ozone concentration; Less by-products	Best for water applications

APPLICATION OF OZONE TECHNOLOGY IN AGRICULTURE

Ozone technology has been used in many aspects of agriculture, such as crop pest control, seed treatment, fruit and vegetable storage and preservation, and livestock and poultry farm disinfection and deodorization as has been reported in the literature (Figure 4).

This technology takes advantage of the broad-spectrum, high-efficiency, non-residual sterilization properties of ozone (*Dourado et al., 2019*), and provides a new direction for the development of green agriculture.

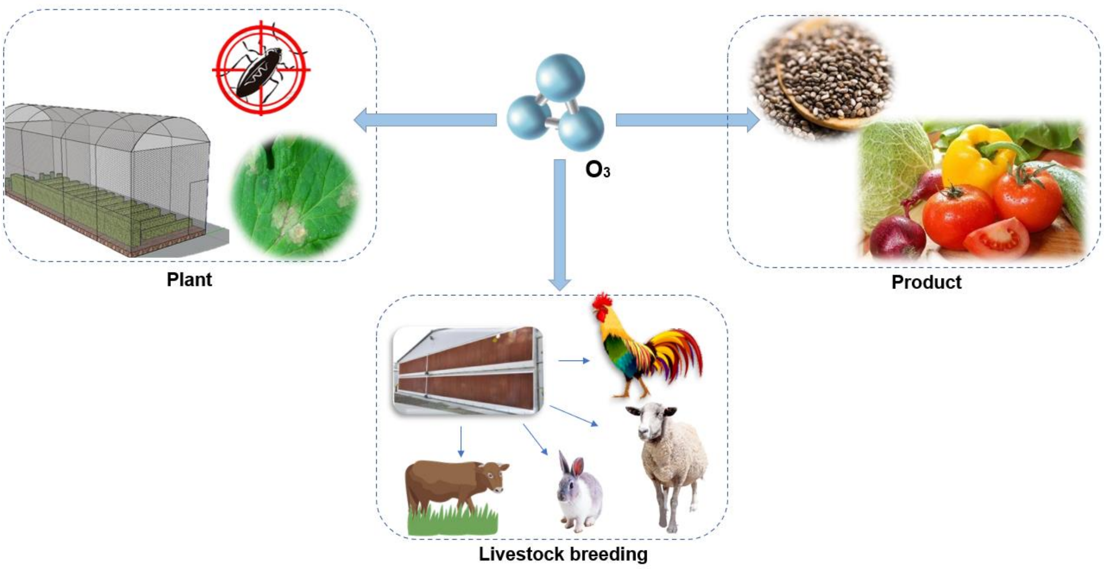

Fig. 4 - Applications of ozone in agriculture reported in the literature

Seed treatment

Seeds are an essential part of agriculture, but they are susceptible to infection in storage and have a high rate of mildew, which often leads to deformed seedlings and dead seeds. Therefore, there is an urgent need to increase grain production by increasing seed germination rates (*Rifna et al., 2019*). Chemical treatments for seeds can cause physiological quality loss. Ozone has many benefits as a substitute for chemicals because it is a strong antimicrobial agent as well as a germination enhancer, which can increase the germination rate of seeds and inhibit the growth rate of surface microorganisms (*Violleau et al., 2008*).

Researchers have studied the effects of ozone treatment on seed germination *(Vazquez-Ybarra J.A.，2015; Abeli T., 2017*). Violleau et al. (*Violleau, 2007*) treated corn seeds with ozone and observed that ozone or oxygen oxidative treatment increased their germination rate. Sudhakar et al. (*Sudhakar et al., 2011*) showed that the application of low doses of ozone in tomato seeds increased the germination rate and produced seedlings with longer roots. Similarly, Normov et al. (*Normov et al, 2020*) found that the roots of ozone-treated maize seeds were twice as long (0.10 m) as the roots of untreated seeds. However, wheat seeds treated with ozone did not show any seminal root length (*Savi G.D., 2014*). Landesmann et al. (*Landesmann et al, 2013*) showed that seeds exposed to 90 parts per billion ozone concentration over a long time exhibited maximum germination when stored at 75% relative humidity and 25°C. Łabanowska et al. (*Łabanowska et al., 2016*) suggested that, at moderate concentrations, ozone has a positive impact on seed grains by prompting the improvement of morphological attributes and enhancing their germination. Lazukin et al. (*Lazukin et al., 2018*) analyzed the morphological characteristics and germination rate of soft spring wheat seeds after treating them with ozone, and found that, although the morphology of the seedlings changed significantly after ozone treatment, seed germination was not affected. Zhang et al. (*Zhang Zhijia, 2019*) used ozone to treat cucumber seeds and showed that low-concentration ozone treatment promoted seed germination, and high-concentration ozone treatment inhibited seed germination. Wu et al. (*Wu et al., 2006*) found that persistent exposure of wheat seeds to ozone gas had unfavorable effects on their germination capacity. Recently, Bataller et al. (*Bataller M, 2020*) confirmed that ozone did not prevent sprouting of Red Scarlet seed potatoes, and showed that the incidence and severity of soft rot (Erwinia ssp.) in inoculated seed potatoes were reduced. They also pointed out that ozone treatment of seeds is a potential alternative to disinfection, but integrated analysis of the seed handling of each crop is required. Mosneaga et al. (*Mosneaga et al., 2020*) treated the seeds of wheat, corn, and beans with ozone, and found that the germination energy increased. They also showed that the growth rate of the ozone-treated wheat was 26 times higher than that of untreated wheat, whereas the growth rate of the ozone-treated corn did not change significantly.

Together, these findings show that the use of ozone to treat seeds before crops are planted can increase the germination rate and inhibit the growth rate of surface microorganisms, confirming that ozone is an effective seed treatment method.

Control of diseases and insect pests

Ozone is a highly active and strong oxidant that is extremely unstable. In the decomposition process, oxygen and free ground state oxygen are released. The free ground state oxygen is also a strong oxidant, which can penetrate the cell wall and oxidize and decompose the oxidase that oxidizes glucose to produce energy for the bacteria, so that the bacteria are inactivated and die. Ozone can directly act on bacteria, fungi, and insects by oxidizing histones, mercaptans, and unsaturated fatty acids, resulting in reduced survival rates and even death (*Komanapalli et al, 1996; Kells et al., 2001*). The feasibility of using ozone to control diseases and insect pests has been the focus of several studies.

Pryor et al. (*Alan Pryor, 1999*) found that ozone reduced the number of root nematodes and bacteria in soil, and increased the yield of tomatoes, strawberries, and carrots. Msayleb et al. *(Msayleb et al., 2011*) studied the killing effect of soil fumigation with ozone gas on nematodes, and showed that ozone was highly lethal to nematodes, whether by gas fumigation or by direct ozonation of samples. Similarly, Mitsugi et al. *(Mitsugi et al., 2017*) proposed the extermination of soil worms and the acceleration of plant growth by the ozone treatment of soil. Veronico et al. (*Veronico P, 2016*) showed that using ozone water to irrigate tomato plants inhibited root nematode production. Mendez et al. (*Mendez and Maier et al., 2003*) reported the efficiency of ozone in controlling insect pests in stored grains. Lemic (*Lemic D., 2020*) demonstrated that ozone had a negative effect on adult wheat weevils, and could cause up to 100% mortality. Lise et al. *(Hansen L.S.,., 2012*) showed that ozonation had great potential as an efficient control method against most insect pests in stored products. In addition to killing insects, ozone can also effectively control crop diseases.

Fujiwara et al. *(Fujiwara and Fujii et al., 2009*) showed that ozone reduced visible physiological disorders in cucumber leaves and had the ability to disinfect powdery mildew, but the concentration of the ozone water that they used was not reported. Hirneisen et al. (*Hirneisen et al., 2011*) treated onion and lettuce with 6.25 ppm ozone for 10 minutes, which reduced the numbers of two different bacteria. Zhang et al. (*Zhang et al., 2011)* found that daily ozone treatment of strawberries for 30 minutes at 0°C inhibited the reduction of ascorbic acid. Lone et al. *(Lone et al., 2019*) reported that ozone techniques had positive results in treating kiwifruit infected with pathogens.

Ozone sterilization for planting in agricultural greenhouses can effectively kill pathogens and the larvae of insect pests. Pesticides have been used for sterilization, disinfection, and pest control in greenhouses, but their repeated use has made pests and pathogens resistant to many pesticides. Furthermore, pesticides can cause widespread pollution of the environment. The use of ozone in greenhouses can control pests and diseases, and does not lead to resistance or cause environmental pollution. The magnitude of reduction in the growth rate of ozone-treated plants appears to depend on the types of pathogens and pests, ozone concentration, and exposure methods and times.

Food preservation

High incidences of foodborne diseases have been associated with contaminated vegetables and fruits, and therefore preventing microbial destruction is essential to achieve the safety and storage stability of food. Traditional processing methods usually sacrifice the sensory attributes and nutritional qualities of the food. The application of chemical fungicides to control post-harvest diseases is increasingly restricted because of concerns about the safety of fungicides and the development of pathogen resistance to many key fungicides. Because consumers increasingly favor fresh foods, alternative technologies are needed to maintain most of the fresh attributes, and ensure the safety and storage stability of food (*Khadre, Yousef et al., 2001*).

Ozone technology provides a new approach to solve the preservation problem of fruits and vegetables. Treating fruits and vegetables with ozone can prolong their storage period, because ozone can kill microorganisms on their surfaces *(Tiwari, Muthukumarappan et al., 2008*) and reduce the breathing intensity of fruits and vegetables, thus slowing the decay process (*Patil S., 2001; Tiwari B.K., 2012*). In 1999, Anglada et al. (*Anglada et al., 1999*) proposed a theoretical mechanism by which ozone destroys ethylene and, subsequently, ozone technology has provided a new way of preserving fruits and vegetables. Muthukumarappan et al. *(Muthukumarappan et al., 2000*) found that the storage life of foods such as beef, chicken, and lamb was prolonged when placed in ozone. Skog et al. (*Skog, 2001*) found that ozone reduced ethylene levels in the air in a cold storage room, and Palou et al. (*Palou et al., 2001*) showed that ozone was effective in removing ethylene from export containers. Karaca et al. (*Karaca et al., 2007*) confirmed that the antiseptic property of ozone was mainly to reduce the production and viability of spores. Wei et al. *(Wei et al., 2011*) studied the effects of ozone treatment on the quality of fresh fruits and the inactivation of natural microflora under different ozone concentrations and concluded that the use of ozone as a disinfectant in the food processing industry needs to be product specific. Venta et al. (*Venta M.B., et al., 2010*) found that the exposure of tomatoes to gaseous ozone not only preserved their sensory attributes but also extended their shelf life. Asokapandian et al. (*Asokapandian Sangamithra, 2018*) used the microbial inactivation effect of ozone to preserve the sensory and nutritive values of foods, and found that even at low concentrations, ozone was very effective against a broad spectrum of microorganisms. Moreover, this method has high practicability, does not leave hazardous residues on food, and because ozone is produced on site, the transportation cost and storage volume of disinfectants are highly reduced.

The efficiency of ozone treatment in reducing microbial counts on fresh produce depends on the ozone dose and on the initial microbial counts/inoculum, as has been demonstrated in many studies (Table 2).

Table 2

Efficiency of ozone treatments against microbial populations on selected fruits and vegetables

Crop	References	State	Treatment(s)	Effect
Carrot	*(Chauhan, 2011)*	Gaseous	9-10ppm/5-15min	*E. coli* decreased by 2.7log CFU;
		Aqueous	10ppm/10min	Yeasts and molds reduced up to 1.92 log CFU
				Standard Plate reduced up to 3.22 log CFU
Tomato	*(Bermúdez-Aguirre, 2013)*	Gaseous	5 ppm/3–15min	*E. coli* decreased by 2.2 log CFU counts
Lettuce	*(Garcia, 2010)*	Aqueous	5ppm/10min	Viable aerobic bacteria and yeast/mold reduced to 1.5 log CFU and 1 log CFU

Crop	References	State	Treatment(s)	Effect
Cucumber	*(Siegel, 1962)*	Aqueous	2.5-5.8 ppm/30min	Psychrotrophic bacteria counts decreased by 1.3 log CFU
Blueberries	*(Bialka, 2007)*	Gaseous	7.9 ppm/32 min	*E. coli* decreased by 2.5 log CFU
		Gaseous	8.9 ppm/32 min	Salmonella decreased by 4.9 log CFU
Apple	*(Yousef, 2001)*	Aqueous	24ppm/1-5min	*E. coli* decreased by 2.6 log CFU
Spinach	*(Klockow P A, 2009; S. M. E. Rahman, 2010)*	Aqueous	5 ppm/0.5-7 min	*E. coli* decreased by 1.22 log CFU
		Gaseous	5-10 ppm/3 days	*E. coli* decreased by 1.8 log CFU

However, ozone can also affect product quality. Sasmita et al. (*Sasmita, 2019*) concluded that the type of ozone treatment and the length of the storage time influenced the texture, color, and weight loss of red cayenne pepper. Together, these findings indicate that the effects of ozone on the sensory (aromatic, color, texture, weight loss) and nutritional (vitamins, antioxidant capacity, biologically active compounds) properties of foods depend on the dosage used.

Disinfection in animal husbandry

The increased awareness of the need to quality control livestock products means the control of livestock and poultry epidemics has become increasingly important. The ability of ozone to disinfect has proven to be very effective in other processes. In breeding environments, bacteria and viruses can breed easily, and ozone technology has a unique role in disinfection and epidemic prevention. Ozone can disperse to every corner of an enclosed space in a short time and instantly kill viruses, bacteria, fungi, and parasites, thereby effectively preventing the infection and transmission of respiratory diseases among livestock and poultry. Ozone also eliminates odors in such spaces and improves the breeding environment (*Vozmilov, Ilimbetov et al., 2016*).

Ozone has 1.5 times the oxidizing potential of chlorine, acts 3000 times faster than chlorine, and does not produce harmful decomposition products (*Troyan, 1989; Horvitz S, 2010*). Restaino et al. *(Restaino et al., 1995*) confirmed the bactericidal action of ozone towards microorganisms, including *Escherichia coli*, a fecal contaminant. Zhu et al. *(Zhu Hanheng et al., 2001*) used ozone in a chicken coop and found that ozone was not only effective in curbing poultry diseases and improving survival rates, but also was pollution- and residue-free, and it provided fresh air for livestock and poultry. Alkoaik (*Alkoaik, 2009*) used an ozone dose of 25 mg/L to treat animal manure and found that it removed the odor; a 66% reduction was observed in a continuous operation. Feng found that ozone directly decomposed ammonia. Reducing ammonia concentrations will only reduce the environmental pollution associated with livestock production but also reduce the incidence of animal diseases *(Feng, 2010*). Di et al. (*Wei Di, 2011*) applied ozone technology to the environmental prevention and control of poultry breeding epidemics and achieved remarkable results. The test results showed that ozone reduced the disease rate of chickens, and the weight of each chicken increased by an average of about 250g. Liu et al. (*Liu Yuhua et al., 2013*) demonstrated a 90% elimination rate of *E. coli* in water by ozone. They turned on the ozone facility at a pig farm and found that ozone broke down 80% of ammonia and 77% of hydrogen sulfide in the air. Lv et al. (*Lv Yanqiu et al., 2018*) found that ozone had a disinfecting effect on both the air and walls in chicken houses. Ozone technology can reduce the use of antibiotics, lower production costs by maintaining clean air quality in chicken houses, and improve the quality of livestock and poultry and their products.

Ozone has numerous potentials to develop the quality of conventional animal husbandry. Compared with traditional disinfection methods that involve spraying insecticides, the broad spectrum of ozone can not only eliminate a variety of pathogens in the environment at the same time but also decompose ammonia, hydrogen sulfide, and other harmful gases and odors in livestock and poultry houses. After sterilization, ozone is converted to oxygen, which increases the oxygen content in livestock and poultry houses and improves the animal living environment.

Other applications

In addition to sterilization and preservation of fruits and vegetables, ozone also is effective in removing pesticide residues in fruits and vegetables. Fruits and vegetables are important components of the human diet, and pesticides are still the main treatment used to control crop diseases. As a result of this treatment, agricultural products often contain significant amounts of pesticide residues (*Jardim and Caldas, 2012*) that can have detrimental effects on human health, including carcinogenesis and abnormal cell development (*Burrows and Canle et al., 2002*).

The elimination of pesticide residues in food to make it safe for human consumption, has been the focus of much research. The efficiency of conventional techniques, such as washing agricultural products with chemicals, depends on, for example, the location of the residues and their water solubility. Such methods do not completely eliminate pesticides *(Lozowicka, Jankowska et al., 2016*). Pesticides are organic compounds, and ozone can react with these compounds by breaking chemical bonds, which produces acids, alcohols, amines, and other small molecules. Most of these products are non-toxic, soluble in water, and can be removed by washing (*Pandiselvam et al., 2017*). Ozone eventually decomposes to oxygen, so the processed products do not contain any harmful residues *(Xiong, 2011*).

Metzger et al. (*Metzger, 2007*) stored waxed navel oranges in an ozone atmosphere and found that malathion (an insecticide) and chlorpyrifos (a pesticide) concentrations were lower (0.18–0.20 ppm [parts per million]) than those in oranges that were stored in air, suggesting that ozone may help reduce such residues on citrus fruits.

Hwang et al. (*Hwang et al., 2001*) showed that mancozeb (a fungicide) residues decreased by 56%–97% and ethylene thiourea was removed completely from fresh apples after ozonated water treatment. Tzortzakis (*Tzortzakis, 2007*) used ozone to treat grapes and strawberries, which inhibited the production of gray mold and effectively prevented fungal diseases in the fruits.

Whangchai et al. (*Whangchai et al., 2011*) suggested that gaseous ozone was more effective than aqueous ozone in degrading chlorpyrifos. Kusvuran et al. (*Kusvuran et al., 2012*) treated the orange matrix with ozone for 5 minutes and were able to remove all chlorothalonil (a fungicide) residues.

Heleno et al. (*Heleno et al., 2014*) concluded that ozone can be used to remove pesticide residues from strawberries without affecting their quality. Balawejder et al. *(Balawejder et al., 2014*) found that the captan (a fungicide) residue was greatly reduced when raspberries and blackcurrants were treated with gaseous ozone.

Karaca (*Karaca, 2019*) found that the butyrate residue was significantly reduced in grapes stored in an ozone-enriched environment (0.64 mg/m−3) but weight loss was less severe for grapes stored in ambient air compared with that for grapes stored in ozone. It was suggested that extra humidification could be done in cold rooms when ozone was used for grape storage.

Wu et al. (*Wu et al., 2019*) showed that the percentage of 10 pesticide residues removed with ozone washing for 15 minutes was significantly higher than it was with ozone washing for 5 minutes. They found the percentage of pesticide residues that was removed depended on the washing solutions and treatment times, as well as the characteristics of the pesticides.

Kusvuran et al. *(Kusvuran et al., 2012)* found that the efficiency of ozone in removing pesticide residues depended on the structural properties of the pesticides and matrices.

Ozone can not only oxidize and degrade pesticide residues on the surfaces of fruits and vegetables, but also can penetrate into the leaves to degrade pesticides. The effects of ozone treatments on the degradation of pesticide residues on the surfaces of fruits and vegetables are shown in Table 3. These findings indicate that ozone cleaning has a significant effect on the removal of pesticide residues.

Table 3

Pesticide degradation by ozone treatment

Fruit/vegetable	References	Pesticide	State	Treatment(s)	Effect (%)
Apple	(Jijun Gong, 2011; Piotr Antos, 2018)	Diphenylamine	Aqueous	16 mg·L^{-1}/20 min	75
		Captan	Gaseous	1 ppm was dosed every 12 h for 1 min up to 84 days	78.9
Citruses	(Kusvuran et al., 2012)	Chlorothalonil	Aqueous	5ppm/10min	100
Strawberry	(Heleno et al., 2014)	Difenoconazole	Gaseous	0.8 mg·L^{-1} /60 min	95
Tomato	(Tawfiq, 2015; Al-Antary, 2018)	Carbosulfan	Aqueous	4 μg·L^{-1}	100
		Myclobutanil	Gaseous	5 ppm /15 min	98
Chili	(Panlop Sintuya, 2018)	Malathion	Aqueous	5.5 g·h^{-1}/30min	68
Carrots	(Lauana Pellanda De Souza, 2018)	Difenoconazole	Aqueous	5 mg·L^{-1}	70.3
			Gaseous	5 mg·L^{-1}	95.3

DISCUSSION

In this review, the current knowledge of the broad social impact of ozone and provided evidence-based data for ozone applications in agriculture was described. Some sterilization methods commonly used in agriculture have adverse effects on human health and the environment, and the use of some chemicals has been restricted. Ozone has the following advantages over conventional agents that can help solve these problems.

High efficiency

Ozone is highly oxidizing and the reaction rate is very fast. At the correct concentrations, ozone can destroy bacterial cells and insect pests within a short time period, thereby eliminating the diseases they cause. Ozone has a broad spectrum and can kill many kinds of pathogens and pests associated with plant diseases, making ozone a highly effective bactericidal and insecticidal reagent.

High cleanliness

Ozone is produced from oxygen in the air. After sterilization, ozone decomposes to oxygen at room temperature because it is extremely unstable. Unlike the traditionally used chemicals, ozone leaves no residue and therefore there is no secondary contamination.

Increased production and improved crop quality

Ozone treatment can significantly improve the safety and quality of fruits and vegetables, including larger fruit, brighter skin surface color, and better flesh taste. Ozone also can degrade pesticide residues on the surfaces of fruits and vegetables, thereby removing harmful chemicals.

Despite the many advantages of ozone, its application in agricultural production still has many limitations. One important aspect is that the concentration of ozone is not easy to control. Although ozone can meet the requirements of agricultural insecticidal sterilization, low ozone concentrations have a limited effect on disease control and high ozone concentrations can lead to electrolyte leakage and membrane damage. At present, it is not possible to precisely control the concentration of ozone released. Furthermore, most of the ozone equipment currently on the market is expensive, which leads to difficulties in promoting ozone technology. Therefore, the development of low-cost ozone sterilization machinery is a good future direction.

CONCLUSIONS

We have argued that ozone sterilization technology has great potential to replace the existing technologies for more sustainable and effective agricultural activities. The ozone characteristics of strong permeability, no residue, and no pollution are the main reasons for the rapid growth of demand for this technology in various fields. The effects of ozone treatments in agriculture depend greatly on the environment and crop types. Some applications of ozone are already in use, whereas other applications require further research to increase trust in the use of ozone. For example, ozone concentrations need to be adjusted according to the tolerance of crops and pests to ozone, so that ozone concentrations are optimized for different environments, different crops, and different pests. Moreover, the influence of high ozone concentrations on crop growth, metabolism, and yield needs to be further clarified. We strongly recommend a planned large-scale experiment to explore the optimal ozone concentrations for use in agriculture.

ACKNOWLEDGEMENT

This study was supported by the National Key R&D Program of China (No. 2020YFD1000300), and the authors are appreciative of the comments from the anonymous reviewers who provided helpful suggestions on improving this paper.

REFERENCES

[1] Abeli T., Guasconi D.B., Mondoni A., Dondi D., Orsenigo S., (2017), Acute and chronic ozone exposure temporarily affects seed germination in alpine plants. *Plant biosystems*, Vol.151, no.2, pp. 304-315.

[2] Achen M., Yousef A.E., (2001), Efficacy of Ozone Against Escherichia coli O157:H7 on Apples. *Journal of Food Science*, Vol.66, no.9, pp. 1380-1384.

[3] Al-Antary T.M., Shaderma A.M., Al-Dabbas M.B., (2018), Ozonation treatment effect on spiked chlorfenapyr pesticide on tomato fruits. *Fresenius Environmental Bulletin*, Vol.2, no.11, pp.7822-7626.

[4] Alkoaik F.N., (2009), Ozone treatment of animal manure for odor control. *American Journal of Environmental Sciences*, Vol.5, no.6, pp.765-771.

[5] Anglada J.M., Crehuet R., Bofill J.M., (1999), The Ozonolysis of Ethylene: A Theoretical Study of the Gas-Phase Reaction Mechanism. *Chemistry A European Journal*, Vol.5, no.6, pp. 1809-1822.

[6] Antos P., Piechowicz B., Gorzelany J., Matlok N., Migut D., Jozefczyk, R., (2018), Effect of Ozone on Fruit Quality and Fungicide Residue Degradation in Apples during Cold Storage. *Ozone: Science & Engineering*, Vol.40, no.6, pp.1-5.

[7] Asokapandian S., Periasamy S., Swamy G.J., (2018), *Fruit Juices*, Chapter 25-Ozone for Fruit Juice Preservation, pp. 511-527.

[8] Balawejder M., Szpyrka E., Antos P., Józefczyk R., Piechowicz B., SadlO S., (2014), Method for reduction of pesticide residue levels in raspberry and blackcurrant based on utilization of ozone. *Ochrona Srodowiska I Zasobów Naturalnych*, Vol.25, no.4, pp.1-5.

[9] Bataller M., Veliz E., Riverol Y., Fernández L.A., Fernández I., (2020), Effect of ozone on sprouting of potato and sugarcane seeds: a sustainable alternative of disinfection. *Ozone Science and Engineering*, Vol.43, no.1, pp.1-10.

[10] Bermúdez-Aguirre D., Barbosa-Cánovas G.V., (2013), Disinfection of selected vegetables under nonthermal treatments: Chlorine, acid citric, ultraviolet light and ozone. *Food Control*, Vol.29, no.1, pp. 82-90.

[11] Bialka K., Demirci A., (2007), Utilization of gaseous ozone for the decontamination of escherichia coli o157:h7 and salmonella on raspberries and strawberries. *Journal of Food Protection*, Vol.70, no,5, pp.1088-1092.

[12] Bialka K.L., Demirci A., (2010), Decontamination of Escherichia coli O157:H7 and Salmonella enterica on Blueberries Using Ozone and Pulsed UV-Light. *Journal of Food Science*, Vol.72, no.9, pp.391-396.

[13] Brodowska A.J., Nowak A., Śmigielski K., (2017), Ozone in the food industry: Principles of ozone treatment, mechanisms of action, and applications: An overview. *Critical reviews in food science and nutrition*, Vol.58, no.13, pp. 2176-2201.

[14] Burrows H.D., Canle L M., Santaballa J.A., Steenken S., (2002), Reaction pathways and mechanisms of photodegradation of pesticides. *Journal of Photochemistry & Photobiology B Biology*, Vol.67, no.2, pp. 71-108.

[15] Cayuela J. A., Vazquez A., Perez A.G., Garcia J.M., (2009), Control of Table Grapes Postharvest Decay by Ozone Treatment and Resveratrol Induction. *Food Science & Technology International*, Vol.15, no.5, pp. 495-502.

[16] Chauhan O.P., Raju P.S., Ravi N., Singh A., Bawa A.S., (2011), Effectiveness of ozone in combination with controlled atmosphere on quality characteristics including lignification of carrot sticks. *Journal of Food Engineering*, Vol.102, no.1, pp. 43-48.

[17] Dajun F., (2010), The effect of ozone disinfection in livestock and poultry house is good (畜禽舍用臭氧消毒效果好), *Hunan Agriculture*, vol.6, pp.22.

[18] Dourado C., Pinto C., Barba, F.J., Lorenzo J.M., Delgadillo I., Saraiva J.A., (2019), Innovative non-thermal technologies affecting potato tuber and fried potato quality. *Trends in Food Science & Technology*, Vol.88, pp. 274-289.

[19] Fujiwara K., Fujii T., Park J., (2009), Comparison of Foliar Spray Efficacy of Electrolytically Ozonated Water and Acidic Electrolyzed Oxidizing Water for Controlling Powdery Mildew Infection on Cucumber Leaves. *Ozone: Science & Engineering*, Vol.31, no.1, pp. 10-14.

[20] Garcia A., Mount J.R., Davidson P.M., (2010), Ozone and Chlorine Treatment of Minimally Processed Lettuce. *Journal of Food Science*, Vol.68, no.9, pp.2747-2751.

[21] Gonçalves A.A., (2009), Ozone: an emerging technology for the seafood industry. B*razilian archives of biology and technology*, Vol.52, no.6, pp. 1527-1539.

[22] Guzel-Seydim Z.B., Greene A.K., Seydim A.C., (2004), Use of ozone in the food industry. *LWT - Food Science and Technology*, Vol.37, no.4 pp. 453-460.

[23] Hanheng Z., (2001), Application of ozone technology in poultry (臭氧技术在家禽中的应用), *China Poultry*, Vol.23, no.7, pp.41.

[24] Hansen L.S., Hansen P., Jensen K.M.V., (2012), Lethal doses of ozone for control of all stages of internal and external feeders in stored products. *Pest Management Science*, Vol.68, no.9, pp. 1311-1316.

[25] Heleno F.F., Queiroz M.E.L.R.D., Neves A.A., Freitas R.S., Faroni L.R.A., Oliveira A.F.D., (2014), Effects of ozone fumigation treatment on the removal of residual difenoconazole from strawberries and on their quality. *Journal of Environmental Science and Health. Part B. Pesticides Food Contaminants and*

Agricultural Wastes, Vol.49, no.2, pp. 94-101.
[26] Hirneisen K.A., Markland S.M., Kniel K.E., (2011), Ozone inactivation of norovirus surrogates on fresh produce. *Journal of Food Protection*, Vol.74, no.5, pp.836-839.
[27] Horvitz S., Cantalejo M.J., Erkan M., Aksoy U., (2010), The Effects of Gaseous Ozone and Chlorine on Quality and Shelf Life of Minimally Processed Red Pepper. *VI International Postharvest Symposium*, pp. 583-589.
[28] Hwang E.S., Cash J.N., Zabik M.J., (2001), Postharvest Treatments for the Reduction of Mancozeb in Fresh Apples. *Journal of Agricultural and Food Chemistry*, Vol.49, no.6, pp. 3127-3132.
[29] Jardim A., Caldas E.D., (2012), Brazilian monitoring programs for pesticide residues in food – Results from 2001 to 2010. *Food Control*, Vol.25, no.2, pp. 607-616.
[30] Jijun Gong, Zhonghai Li, Haiyan Zhong, Jing Tang., (2011), Ozone/ultrasound degradation effect on residual pesticides in commercially available apples. *IEEE - 2011 Semiconductor Conference Dresden: Technology, Design, Packaging, Simulation and Test* (Dresden).
[31] Karaca H., (2019), The Effects of Ozone-Enriched Storage Atmosphere on Pesticide Residues and Physicochemical Properties of Table Grapes. *Ozone Science and Engineering: The Journal of the International Ozone Association*, Vol.41, no.5, pp.404-414.
[32] Karaca H., Velioglu Y.S., (2007), Ozone Applications in Fruit and Vegetable Processing. *Food Reviews International*, Vol.23, no.1, pp. 91-106.
[33] Khadre M.A., Yousef A.E., Kim J.G., (2001), Microbiological Aspects of Ozone Applications in Food: A Review. *Journal of food science*, Vol.66, no.9, pp. 1242-1252.
[34] Klockow P.A., Keener K.M., (2009), Safety and quality assessment of packaged spinach treated with a novel ozone-generation system. *LWT - Food Science and Technology*, Vol.42, no.6, pp. 1047-1053.
[35] Komanapalli I.R., Lau B.H., (1996), Ozone-induced damage of Escherichia coli K-12. *Applied Microbiology & Biotechnology*, Vol.46, no.5-6, pp. 610-614.
[36] Kusvuran E., Yildirima D., Mavruk F., Ceyhanb M., (2012), Removal of chloropyrifos ethyl, tetradifon and chlorothalonil pesticide residues from citrus by using ozone. *Journal of Hazardous Materials*, Vol.241-242, pp. 287-300.
[37] Łabanowska M., Kurdziel M., Filek M., (2016), Changes of paramagnetic species in cereal grains upon short-term ozone action as a marker of oxidative stress tolerance. *Journal of Plant Physiology*, Vol.190, pp. 54-66.
[38] Landesmann J.B., Gundel P.E., Martínez-Ghersa M.A., Ghersa C.M., (2013), Ozone Exposure of a Weed Community Produces Adaptive Changes in Seed Populations of Spergula arvensis. *Plos One*, Vol.8, no.9, pp.1-11.
[39] Lazukin A., Serdukov Y., Pinchuk M., Stepanova O., Krivov S., Lyubushkina I., (2018), Treatment of spring wheat seeds by ozone generated from humid air and dry oxygen. *Research in Agricultural Engineering*, Vol.64, no.1, pp.34-40.
[40] Lemic D., Jembrek D., Baok, R., Ivkovic I.P., (2020), Ozone Effectiveness on Wheat Weevil Suppression: Preliminary Research. *Insects (Basel, Switzerland)*, Vol.10, no.10, pp. 357.
[41] Lone S.A., Sathya R., Davoodbhasha M.A., Srinivasan H., 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*, Vol.20, pp. 101212.
[42] Lozowicka B., Jankowska M., Hrynko I., Kaczynski P., (2016), Removal of 16 pesticide residues from strawberries by washing with tap and ozone water, ultrasonic cleaning and boiling. *Environmental Monitoring and Assessment*, Vol.188, no.1, pp.51.
[43] Mendez F., Maier D.E., Mason L.J., Woloshuk C.P., (2003), Penetration of ozone into columns of stored grains and effects on chemical composition and processing performance. *Journal of Stored Products Research*, Vol.39, no,1, pp. 33-44.
[44] Metzger C., Barnes J.D., Singleton I., Andrew P., (2007), Effect of low-level ozone-enrichment on the quality and condition of citrus fruit under semi-commercial conditions. *IOA Conference and Exhibition*, Vol 11, pp.1-7, Valencia, Spain.
[45] Mitsugi F., Abiru T., Ikegami T., Ebihara K., Nagahama K., (2017), Treatment of Nematode in Soil Using Surface Barrier Discharge Ozone Generator. *IEEE Transactions on Plasma Science*, Vol,45, no.12, pp. 3076-3081.

[46] Mosneaga A., Nedeff V., Sandu I., Lozovanu P., Sandu I.G., (2020), Utilization of Ozone and Composite Materials in the Seed Treatment to Stimulate the Germination and Growth of Agricultural Crops. *Revista de Chimie -Bucharest- Original Edition*, Vol.71, no.2, pp. 365-370.
[47] Msayleb N., Ibrahim S., (2011), Treatment of Nematodes with Ozone Gas: A Sustainable Alternative to Nematicides. *Physics Procedia*, Vol.21, pp. 187-192.
[48] Muthukumarappan K., Halaweish F., Naidu A.S., (2000), *Natural Food Anti-Microbial Systems*, "Chapter-29 Ozone", CRC Press LLC.
[49] Normov D., Evgenii Chesniuk, Shevchenko A., Normova T., Goldman R., Pozhidaev D., Bohinc T., Trdan S., (2020), Does ozone treatment of maize seeds influence their germination and growth energy? *Acta agriculturae Slovenica*, Vol.114, no.2, pp. 251-258.
[50] Palou L., Smilanick J.L., Crisosto C.H., Mansour M., (2001), Effect of gaseous ozone exposure on the development of green and blue molds on cold stored citrus fruit. *The American Phytopathological Society*, Vol.85, no.6, pp. 632-638.
[51] Pandiselvam R., Sunoj S., Manikantan M.R., Kothakota A., Hebbar K B., (2017), Application and Kinetics of Ozone in Food Preservation. *Ozone: Science & Engineering*, Vol.39, no.2, pp. 115-126.
[52] Patil S., Valdramidis V. P., Tiwari B. K., Cullen P. J., Bourke P., (2011), Quantitative assessment of the shelf life of ozonated apple juice. *European food research & technology*, Vol.232, no.3, pp. 469-477.
[53] Patil S., Smith S.J., (2001), Irradiation and Food Safety. *FOOD TECHNOLOGY*, Vol.58, no.11, pp.48-55.
[54] Pryor A., (1999), Results of two years of field trials using ozone gas as a soil treatment agent. *Annual International Conference on Methyl Bromide Alternatives and Emissions Reductions*.US EPA and USDA San Diego, USA.
[55] Restaino L., Frampton E.W., Hemphill J.B., Palnikar P., (1995), Efficacy of ozonated water against various food-related microorganisms. *Applied and Environmental Microbiology*, Vol.61, no.9, pp. 3471-3475.
[56] Rifna E.J., Ramanan R., Radhakrishnan M., (2019), Emerging technology applications for improving seed germination. *Trends in Food Science & Technology*, Vol.86, pp. 95-108.
[57] Roustan M., Mallevialle J., Jones J.P., (2008), Mass Transfer of Ozone to Water: A Fundamental Study. *Ozone Science & Engineering*, Vol.2, no.4, pp. 337-344.
[58] Rahman S., Tian D., (2010), Inactivation effect of newly developed low concentration electrolyzed water and other sanitizers against microorganisms on spinach. *Food Control*, Vol.21, no.10, pp. 1383-1387.
[59] Sasmita E., Restiwijaya M., Yulianto E., Yuliani F.A., Kinandana A.W., (2019), Effect of ozone technology applications on physical characteristics of red cayenne pepper (Capsicum frutescens L.) preservation. *Journal of physics. Conference series*, Vol.1217, no.1, pp. 12007.
[60] Savi G.D., Piacentini K.C., Bittencourt K.O., Scussel V.M., (2014), Ozone treatment efficiency on Fusarium graminearum and deoxynivalenol degradation and its effects on whole wheat grains (Triticum aestivum L.) quality and germination. *Journal of Stored Products Research*, Vol.59, pp. 245-253.
[61] Siegel S.M., (1962), Protection of Plants Against Airborne Oxidants: Cucumber Seedlings at Extreme Ozone Levels. *PLANT PHYSIOLOGY*, Vol.3, no.37, pp. 261-266.
[62] Sintuya P., Narkprasom K., Jaturonglumlert S., Whangchai N., Peng-Ont D., Varith J., (2018), Effect of Gaseous Ozone Fumigation on Organophosphate Pesticide Degradation of Dried Chilies. *Ozone: Science & Engineering*, Vol.40, no.6, pp. 473-481.
[63] Skog L.J., Chu C.L., (2011), Effect of ozone on qualities of fruits and vegetables in cold storage. *Canadian Journal of Plant Science*, Vol.81, no.4, pp. 773-778.
[64] Souza L.P.D., Lêda R.A.F., Heleno F.F., Pinto F.G., Queiroz M.E.L.R.D., Prates L.H.F., (2017), Ozone treatment for pesticide removal from carrots: Optimization by response surface methodology. Food Chemistry, Vol.243, pp. 435-441.
[65] Stephen A.K., Linda J.M., Dirk E.M., Charles P.W., (2001), Efficacy and fumigation characteristics of ozone in stored maize. *Journal of stored products research*, Vol.37, no.4, pp. 371-382.
[66] Sudhakar N., Nagendra-Prasad D., Mohan N., Hill B., Gunasekaran M., Murugesan K., (2011), Assessing Influence of Ozone in Tomato Seed Dormancy Alleviation. *American Journal of Plant Sciences*, 2011. Vol.2, no.3, pp. 443-448.
[67] Tapp C., Rice R.G., (2012), *Ozone in food processing*, "Wiley", Chapter 4.

[68] Tawfiq M., Al- Antary T.M., Al-Dabbas M.M., Shaderma A.M., (2015), Evaluation of three treatments on carbosulfan removal in tomato juice. *Fresenius Environmental Bulletin*, Vol.24, no.3, pp.733-739.
[69] Tiwari B.K., Muthukumarappan K., (2008), Modelling colour degradation of orange juice by ozone treatment using response surface methodology. *Journal of Food Engineering*, Vol.88, no.4, pp. 553-560.
[70] Tiwari B.K., Muthukumarappan K., (2012), *Ozone in Food Processing*. Chapter 5 "Ozone in Fruit and Vegetable Processing", John Wiley & Sons, Ltd.
[71] Troyan, Jerrold J., Troyan B., Hansen, S. P., (1989), Treatment of microbial contaminants in potable water supplies. Noyes Data Co.
[72] Tzortzakis N., Singleton I., Barnes J., (2007), Deployment of low-level ozone-enrichment for the preservation of chilled fresh produce. *Postharvest Biology and Technology*, Vol.43, no.2, pp. 261-270.
[73] Vazquez-Ybarra J.A., Pena-Valdivia C.B., Trejo C., Villegas-Bastida A., Sanchez-Garcia P., (2005), Promoting growth of lettuce plants (Lactuca sativa L.) with sublethal ozone doses applied to culture medium. *Revista fitotecnia mexicana publ. por la Sociedad Mexicana de Fitogenetica*, Vol.38, no.4, pp.405-413.
[74] Venta M.B., Broche S.S.C., Torres I.F., Pérez M.G., Lorenzo E.V., Rodriguez Y.R., (2010), Ozone Application for Postharvest Disinfection of Tomatoes. *Ozone: Science & Engineering,* Vol.32, no.5, pp. 361-371.
[75] Veronico P., Paciolla C., Sasanell N., Leonardis S.D., Melillo M.T., (2016), Ozonated water reduces susceptibility in tomato plants against Meloidogyne. *Molecular Plant Pathology*, Vol.18, no.4, pp.529-539.
[76] Violleau F., Hadjeba K., Albet J., Cazalis R., Surel O., (2007), Increase of corn seeds germination by oxygen and ozone treatment, *IOA Conference and Exhibition Valencia*, pp. (3-4)1-6, Spain.
[77] Violleau F., Hadjeba K., Albet J., Cazalis R., Surel O., (2008), Effect of Oxidative Treatment on Corn Seed Germination Kinetics. *Ozone: Science & Engineering*, Vol.30, no.6, pp. 418-422.
[78] Vozmilov A.G., Ilimbetov R., Astafev D.V., (2016), The usage of ozone in agriculture technological processes. *2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, IEEE.
[79] Wei Di., (2011), Experiment of O_3 sterilization and its application in cage breeding (O_3灭菌试验及在舍饲养殖中的应用), *Agricultural Science & Technology and Equipment*, Vol.4, no.202, pp.75-77.
[80] Whangchai K., Uthaibutra J., Phiyanalinmat S., Pengphol S., Nomura N., (2011), Effect of Ozone Treatment on the Reduction of Chlorpyrifos Residues in Fresh Lychee Fruits. *Ozone: Science & Engineering*, Vol.33, no.3, pp. 232-235.
[81] Wu Jiangning, Doan H., Cuenc M.A., (2006), Investigation of gaseous ozone as an anti-fungal fumigant for stored wheat. *Journal of Chemical Technology & Biotechnology*, Vol.81, no.7, pp. 1288-1293.
[82] Xiaona Zhang, Zide Zhang, Lei Wang, Zhenliang Zhang, Jing Li, Congzhi Zhao., (2011), Impact of ozone on quality of strawberry during cold storage. *Frontiers of Agriculture in China*, Vol.5, no.3, pp. 356-360.
[83] Yanqiu Lv, Dongfeng Huang, Xingang Yang., (2018), Ozone Disinfection Test in Chicken House. *Animal husbandry and feed science*, Vol.10, no.02, pp. 97-98.
[84] Yangliu Wu, Quanshun An, Dong Li., Jun Wu, Canping Pan., (2019), Comparison of Different Home/Commercial Washing Strategies for Ten Typical Pesticide Residue Removal Effects in Kumquat, Spinach and Cucumber. *Annals of the American Thoracic Society*, Vol.16, no.3, pp. 1-20.
[85] Yuhua Liu., (2013), Application of Ozone Disinfection Technologies in Livestock and Poultry Breeding. (臭氧杀菌消毒技术在畜禽养殖中的应用), *Agricultural Engineering*, Vol.3 (S1), pp. 45-46+28.
[86] Zhenglong Xiong, Xiang Cheng, Dezhi Sun., (2011), Pretreatment of heterocyclic pesticide wastewater using ultrasonic/ozone combined process. *Journal of Environmental*, Vol.23, no.5, pp. 725-730.
[87] Zhang Zhijia, Liu Hongyan, Zhai Haixiang, Zhang Lina, Jiao Caiju, (2019), Effect of ozone treatment on germination of tomato and cucumber seeds (臭氧处理对番茄和黄瓜种子萌发的影响), *Journal of Northwest A & F University (Natural Science Edition)*, Vol.47, no.9, pp. 98-111.