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OZONE AS AN EMERGING TECHNOLOGY IN THE CONTROL OF FUNGI AND INSECTS IN RICE STORAGE: A REVIEW

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Abstract
Rice storage losses due to fungal contamination and insect infestation constitute a major threat to food security worldwide. Conventional control methods such as chemical fumigants and pesticides, has raised concerns regarding residues, resistance development, and environmental impact. Ozone (O_3), a powerful oxidizing agent that decomposes rapidly into oxygen, has emerged as a promising alternative for postharvest pest and pathogen management. This review evaluates the potential of ozone technology in rice storage, focusing on its mechanisms of action against fungi and insects, application methods, effects on grain quality. Evidence from laboratory and pilot-scale studies indicates that ozone can effectively suppress storage fungi, reduce mycotoxin contamination, and control insect pests without leaving harmful residues. Despite these advantages, challenges related to dosage optimization, safety, and large-scale implementation remain. Overall, ozone represents a sustainable and innovative technology for improving rice storage safety and reducing postharvest losses.

Keywords: Ozone; rice storage; fungi; insects; postharvest management; sustainable technology

Introduction

Rice (*Oryza sativa*) is one of the most important foods in the human diet, being consumed by approximately 75% of the world's population and the demand for the production of rice is increasing with the growth in the global population (Rosefl & Marco, 2008; Savi et al., 2018; Chandravarnan & Agyei & Ali, 2022). Rice grains stand out for being good source of carbohydrate (75–80%), with a moderate amount of protein (7%) and fat (Fresco, 2005). In addition, rice provides minerals such as magnesium, manganese, selenium, iron and phosphorus, as well as the vitamins thiamin, niacin, and folic acid (Fukagawa & Ziskha, 2019).

According to FAO (2025), world rice production was 799 million tons in 2023. The Asian continent produces more than 89.6% of rice globally with China and India being the main rice producing countries, constituting 51.6% of world production (FAO, 2025). Outside the continent of Asia, Brazil, stands out as an important producer of rice with 10.6 million tons for the 2023/2024 harvest (CONAB, 2025). In Africa Nigeria is the largest producer of rice with an estimated 8.7 million tons harvested in 2024 – 2025 (The African Exponent, 2025)

Rice crop is largely cultivated in subtropical environments, normally in conditions considered favorable for fungal growth due to high temperature and relative humidity, mainly from the genera *Aspergillus*, *Fusarium*, and *Penicillium* (Reddy, Reddy & Muralidharan, 2009; Chandravarnan & Agyei & Ali, 2022). Regarding storage, rice grains are an excellent food source for fungal growth (Al-Zoreky & Saleh, 2019), including those that produce mycotoxins. Mycotoxins are secondary

metabolites capable of causing diseases in humans and animals (Coppock & Dziwenka, 2014). The presence of mycotoxigenic fungi has been reported in several regions of the world (Al-Husnain & Al-Kahtani, 2019; Zhao et al., 2019). Among the main mycotoxins that can be produced in rice, there are aflatoxins, fumonisins, ochratoxins, deoxynivalenol, zearalenone, citrinin, sterigmatocystin, cyclopiazonic acid, patulin, gliotoxin and trichothecenes (Santos et al., 2022; Chandravarnan, Agyei & Ali, 2024). Rice is also susceptible to insect attacks, which are responsible for qualitative and quantitative losses in stored grains. Among the insects that can cause losses in rice grains is rice weevils (*Sitophilus oryzae*), considered a primary stored-grain insect in warm climate areas, therefore, they can attack sound and undamaged grain (Batta, 2004; Doherty, Sun & Wilson, 2023). As regards the control of these insects, fumigation with phosphine is the main form of control with regulations in several countries (Doherty, Sun & Wilson, 2023). However, there is growing concern about the resistance of insects to this fumigant, especially since there is still no suitable substitute fumigant (Pimentel et al., 2009; Pimentel et al., 2010; Hagstrum, Phillips & Cuperus, 2012; Nayak et al., 2020).

In view of this challenge, ozonation has been presented as an alternative for the preservation of stored grains. Ozone has been tested for the control of both microorganisms and insects. This gas is a strong oxidizing agent that is effective against many types of microorganisms that deteriorate and/or contaminate fruits, vegetables, grains, and their products (Kaur et al., 2022; Pandiselvam et al., 2022; Premjit, Sruthi, Pandiselvam, & Kothakota, 2022; Okolo et al., 2023; Uzoma et al., 2024). It is important to note that the management of microbial contamination, including metabolites such as mycotoxins, is a primary concern of the modern food industry. In this context, it is crucial to develop green and eco-friendly strategies to reduce the amount of agricultural products losses and contamination with pesticides residues or mycotoxins in foods and feeds (Okolo et al., 2023; Wang et al., 2019). Regarding the control of insect pests of stored grains, the effectiveness of ozone gas in controlling *S. zeamais*, *S. oryzae*, *Tribolium castaneum*, *Cryptolestes ferrugineus*, *Ephestia kuehniella*, among others, was verified. (Rozado et al., 2008; Sousa et al., 2008; Hansen et al., 2013; Jian et al., 2013; Amoah & Mahroof, 2019; Silva et al., 2020; Uzoma et al., 2024). This review critically examines the role of ozone in controlling fungi and insects in rice storage systems.

Generation of Ozone

On ozone generation, a diatomic oxygen molecule must first be split (Gonçalves, 2009). The resulting free radical oxygen is thereby free to react with diatomic oxygen to form the triatomic ozone molecule (Langlais et al., 1991; Greene et al., 2012). Electric discharge in oxygen (or air) and irradiation of oxygen (air) with short-wavelength ultraviolet (UV; 188 nm wavelength) rays produce ozone (Takeuchi, 2005). Ozone is generated commercially within the food industry by one of two generally accepted procedures: by passing an oxygen-containing gas through either a source of ultraviolet radiation (UV; photochemical method) (Dohan and Masschelein, 1987; Rice et al., 2006) or a high-energy electrical field (corona discharge - CD) (Langlais et al., 1991). On a commercial scale, the most widely used method is corona discharge. (Guzel-Seydim et al., 2004). Ozone has been used for decades in many countries and is generally recognized as safe (GRAS) (Kim et al., 1999). Ozone (ozone gas or ozonated water) is effective against the majority of microorganisms tested by numerous research groups (Kim et al., 1999). It has stronger antimicrobial activity than chlorine and is considered a broad-spectrum antimicrobial agent that acts against a variety of foodborne pathogens (Priyanka et al., 2014). Relatively low concentrations and reduced contact time are effective to inactivate bacteria, fungi, yeasts, parasites, and food viruses and can be applied to food in gaseous

form or dissolved in water (Kim et al., 2003; Zhang et al., 2011; Alwi and Ali, 2014; Ferreira et al., 2017). However, the rates of inactivation are dependent on oxidizable organic substances in the medium (Khadre et al., 2001). Susceptibility of microorganisms to ozone also varies with the physiological state of the culture, pH of the medium, temperature, humidity, and presence of additives, such as acids, surfactants, and sugars (Kim et al., 1999).

Challenges of Rice storage pests in Nigeria

In Nigeria, rice storage faces significant challenges from fungal contamination and insect infestation, both of which lead to substantial economic losses and health risks through mycotoxin production (Tang et al., 2019). Research indicates that these issues are exacerbated by high tropical temperatures, relative humidity, and rudimentary post-harvest practices (Ekpakpale et al., 2021). Stored rice in Nigeria is frequently contaminated by a variety of fungi, many of which are mycotoxigenic. The most prevalent genera identified in Nigerian rice include *Aspergillus* (approx. 81%), *Penicillium* (15.4%), and *Fusarium* (Ekpakpale et al., 2021; Tang et al., 2019). Out of this genera the dominant species identified from Nigerian rice samples include *Aspergillus flavus, Fusarium moniliforme , F. solani* , and *Curvularia oryzae* (Christian Chukwunenye et al., 2018; Ekpakpale et al., 2021). The contamination by these fungi has led to the accumulation of hazardous mycotoxins, particularly *Aflatoxins, Fumonisins, and Zearalenone* (Tang et al., 2019). Studies in Ondo State found that over 40% of tested food samples exceeded the 10µg/kg threshold for total aflatoxins adopted in Nigeria (Ekpakpale et al., 2021).2.

Stored grains in Nigeria host a diverse range of insects that cause physical damage and facilitate fungal entry. The primary pests affecting stored rice in Nigeria are the rice weevil (*Sitophilus oryzae*), maize weevil (*Sitophilus zeamais*), lesser grain borer (*Rhyzopertha dominica*), and red flour beetle (*Tribolium castaneum*) (Ojo & Omoloye, 2021). Other significant species include the rusty grain beetle (Cryptolestes ferrugineus) and parasitic wasps such as Theocolax elegans (Ojo & Omoloye, 2021). These insects can reduce yields by up to 50% and are often more prevalent when grain moisture exceeds 14% (Tang et al., 2019).

Control and Management Strategies by researchers has focused on both traditional, chemical methods and emerging eco-friendly alternatives as summarized in the table 1 below

Table 1

Method	Description	Effectiveness/Findings
Controlled Atmosphere	Use of Inert Atmosphere Metal Silos (IAMS) with nitrogen gas.	Achieved 100% mortality of all insect life stages and inhibited mold growth for up to 12–48 months (FAO AGRIS, 2021).
Botanical Extracts	Use of plant-derived oils or powders like *Pterocarpus santalinoides* or Basil.	Basil-fortified rice acts as a moderate repellent; *P. santalinoides* oil showed significant mortality rates against *S. zeamais* (Ekeh et al., 2018; Lampiri et al., 2023).
Hermetic Systems	Packaging rice in airtight containers or hermetic bags.	Effectively reduces fungal proliferation and insect respiration by limiting oxygen (Tang et al., 2019).
Cultural Practices	Improving physical grain quality by removing impurities and maintaining moisture below 14%.	Reducing impurities and "chalky" grains directly correlates with lower aflatoxin levels (Tang et al., 2019).

Other control and management application in which the use of Phosphine was adopted, it was discovered that the rice husk has a high phosphine adsorption capacity, influencing the gas concentration during fumigation and potentially leading to inefficient fumigation. Additionally, the high sorption of rice husk results in a higher residue of phosphine in the grain (Pereira et al., 2024). There is also, a growing concern about the resistance of insects to phosphine fumigant, especially since there is still no suitable substitute fumigant (Pimentel et al., 2009; Pimentel et al., 2010; Hagstrum, Phillips & Cuperus, 2012; Nayak et al., 2020). This challenge, has led to the adoption of Ozonation as an alternative for the preservation of stored grains. Ozone has been tested for the control of both microorganisms and insects.

The Effects of Ozone on Rice Storage Pests

Researchers have carried out an extensive work which, highlights ozone **(**O_3**)** as a highly effective, eco-friendly fumigant for removing storage pests in rice and other grains. Its main advantage is its ability to decompose rapidly into oxygen, leaving no chemical residues on the food product thereby making it safe (Tiwari et al., 2010; Lemic et al., 2019). Ozone is toxic to major rice pests, including the Rice Weevil (*Sitophilus oryzae*) and the Lesser Grain Borer (*Rhyzopertha dominica*) (Lemic et al., 2019; Dong et al., 2022). It affects insects by damaging cell membranes, respiratory tissues and disrupting metabolic processes causing fatal oxidative stress (E et al., 2017). Exposure of the insect to ozone can result in reduced feeding, impaired reproduction, and mortality, particularly in confined storage environments (Kells et al., 2001). However, insect mortality depends on ozone concentration, exposure duration, and life stage, with eggs generally being more tolerant than adults (Phillips & Throne, 2010).

Ozone inactivates fungi primarily through oxidative damage to cell membranes, enzymes, and nucleic acids. This leads to leakage of cellular contents, inhibition of spore germination, and suppression of mycelial growth (Suslow, 2004). Several studies have reported significant reductions in *Aspergillus flavus* and *Penicillium* spp. populations on stored grains following ozone exposure (McDonough et al., 2011). In addition, to inhibiting fungal growth, ozone can directly degrade mycotoxins such as aflatoxin B_1 through oxidation reactions, reducing their toxicity (Proctor et al., 2004; Tiwari et al., 2010).

Ozone is particularly valuable because it is effective against pest strains that have developed resistance to traditional phosphine fumigants (E et al., 2017; Dong et al., 2022). In addition to killing insects, ozonation can degrade pesticide residues (such as bifenthrin and deltamethrin) by over 90% and eliminate fungal contaminants like *Aspergillus* and *Penicillium* (de Ávila et al., 2017; Santos et al., 2016). Find in table 2 a summary of some other significant research findings from different authors

Table 2

Primary Focus	Key Findings	Source
Pest Suppression	Ozone effectively kills *Sitophilus spp.* with 100% mortality in 3–4 hours of exposure.	(E et al., 2017)
Residue Removal	Ozonation at 3 mg/L for 10 hours removed ~92% of insecticide residues in rice without altering water content.	(de Ávila et al., 2017)
Fungal Control	Complete inhibition of *Aspergillus* and *Penicillium* in rice grains was achieved after 60 hours of ozonation.	(Santos et al., 2016)
Grain Quality	Studies show that ozone treatment generally does not negatively impact the milling yield or nutritional quality of the rice.	(Tiwari et al., 2010; de Ávila et al., 2017)

The most widely used application of ozone in the control of rice storage pest is gaseous ozone. It can be introduced into silos or warehouses, allowing penetration into intergranular spaces where insects and fungal spores reside (McDonough et al., 2011). The use of continuous or intermittent circulation of ozonated air helps maintain low microbial and insect populations and improves overall storage hygiene (Mendez et al., 2003).

At appropriate concentrations, ozone does not significantly affect milling quality, appearance, or cooking properties of rice (McDonough et al., 2011). Nevertheless, excessive ozone exposure may promote lipid oxidation, potentially affecting aroma and sensory quality (Tiwari et al., 2010).

Conclusion

Ozone is a promising emerging technology for controlling fungi and insects in rice storage. Its strong oxidative capacity, absence of chemical residues, and broad-spectrum efficacy make it an attractive alternative to conventional fumigants particularly in situations where insects have become resistant to Phosphine fumigant. With continued research and technological refinement, ozone could play a significant role in sustainable postharvest rice management in the effective control and management of storage pest in rice

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