Kinetics of the ozone gas reaction at different flow rates in popcorn kernels and application for controlling *Sitophilus zeamais*

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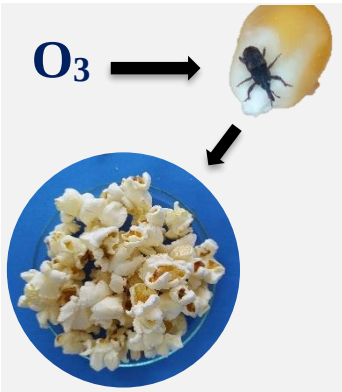

Popcorn kernels are vulnerable to infestation by insects common to grains and their byproducts, particularly those of the genus *Sitophilus*. Ozone gas has emerged as an effective alternative for controlling insect pests and fungi in stored goods. The present study aimed to (i) characterize the decomposition reaction kinetics of ozone gas at different flow rates; (ii) evaluate the mortality rate of adult *S. zeamais* and the volume expansion of popcorn kernels after exposure to ozone gas. Grains treated with 2.5 mg L^{-1} ozone gas at specific flow rates of 0.23, 0.35, and 0.73 m^3 min t^{-1} reached saturation after 180.11, 139.17, and 87.66 h, respectively. Ozone gas exhibited insecticidal potential at all tested flow rates and did not compromise the volume expansion of the popcorn kernels.

Introduction

Popcorn (*Zea mays everta* Sturt.) (Poaceae) is mainly produced in the Americas, primarily for human consumption. It has excellent nutritional properties, and its demand has increased in recent years [1]. Popcorn kernels are vulnerable to insects that commonly infest grains and their byproducts, particularly those of the genus *Sitophilus* (Coleoptera: Curculionidae) [2]. Phosphine gas is usually applied to control these insects, but its continuous and indiscriminate use has caused the selection of more resistant populations [3]. On the other hand, ozone gas has emerged as an effective alternative against insect pests and fungi in stored goods [4,5].

Despite the diffusive behavior of ozone, scientific investigations demonstrated that its application to stored goods yields satisfactory results in pest management when the gas is transported via forced convection throughout the grain mass [6].

The objectives of the present work were the following: (i) to characterize the decomposition reaction kinetics of ozone gas at different flow rates; (ii) to evaluate the mortality of *S. zeamais* adult individuals and the volume expansion of popcorn kernels after exposure to ozone gas.

Material and Methods

Popcorn kernels were sourced from local supermarkets (Viçosa, Minas Gerais, Brazil). The samples were homogenized and stored at 5 °C prior to the experiments, during which the grains were exposed to ozone (2.5 mg L^{-1}) or oxygen (control). Ozone gas was obtained with an ozone generator model M10 (myOZONE, São Paulo, Brazil). It was produced from compressed oxygen (99.99% minimum purity) at specific flow rates of 0.23, 0.35, and 0.73 m^3 min t^{-1}. The ozone gas was evenly distributed inside a cylindrical PVC column dimensioned 0.12 m in height and 0.2 m in diameter. Insect mortality was assessed during the exposure periods required to saturate the grain mass with ozone gas. To accomplish that, three cylindrical cages (6.5 cm × 3.5 cm), each confining thirty *S. zeamais* adult individuals and 50 g of popcorn kernels, were placed on the upper part of the cylindrical column and enclosed with grains. Mortality was assessed 24, 48, 72, and 96 h after exposure to ozone gas. The popping expansion volume [7] was examined to appraise the quality of the kernels.

Results and Discussion

Figure 1 presents the residual ozone concentration curves as a function of time.

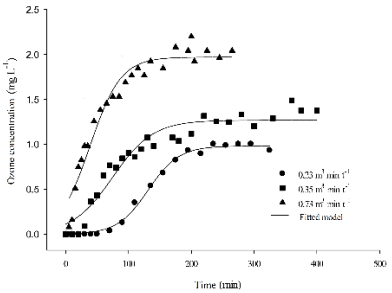

Figure 1. Residual concentration of ozone gas as a function of time at specific flow rates of 0.23, 0.35, and 0.73 m^3 min t^{-1}

The grains treated with ozone gas at 2.5 mg L^{-1} and specific flow rates of 0.23, 0.35, and 0.73 m^3 min t^{-1} reached saturation after 180.11, 139.17, and 87.66 h, respectively. Utilizing higher specific flow rates results in the grain mass reaching saturation more quickly (Figure 1). However, this comes with a greater demand for oxygen to supply ozone

production, thus increasing the costs — especially if the ozone generation system requires industrial oxygen as input. Conversely, applying lower specific flow rates prolongs the time to saturate the grain mass. Table 1 contains the average mortality (%) of *S. zeamais* adult individuals after treatment with ozone gas at 2.5 mg L^{-1} and specific flow rates of 0.23, 0.35, and 0.73 m^3 min^{-1} t^{-1}. Ozone completely controlled the insects when applied at a specific flow rate of 0.73 m^3 min^{-1} t^{-1}. Table 2 compares the average volume expansion for the ozone and control treatments. No statistical difference was detected between the control treatment and the kernels exposed to ozone at 2.5 mg L^{-1} at any of the specific flow rates evaluated, considering a 5% probability level. This result was similar to the findings of other investigations [8].

Table 1. Average mortality (%) of *S. zeamais* adult individuals after treatment with ozone gas at 2.5 mg L^{-1} and specific flow rates of 0.23, 0.35, 0.73.

Specific flow rate (m^3 min^{-1} t^{-1})		Mortality (%)			
		24 h	48 h	72 h	96 h
0.23	Control	0.00 ± 0.00	0.00 ± 0.00	1.57 ± 2.35	1.57 ± 2.35
	Ozone	47.78 ± 6.94	47.78 ± 6.94	61.11 ± 12.62	73.33 ± 11.54
0.35	Control	0.00 ± 0.00	0.00 ± 0.00	1.11 ± 1.92	1.11 ± 1.92
	Ozone	63.33 ± 8.82	65.56 ± 11.71	65.56 ± 11.71	96.67 ± 3.33
0.72	Control	1.11 ± 1.92	2.22 ± 3.84	2.22 ± 3.84	2.22 ± 3.84
	Ozone	68.89 ± 15.39	72.22 ± 12.62	83.33 ± 13.33	100.00 ± 0.00

There was a significant difference between each treatment and its corresponding control for all specific flow rates, according to the F test at a 5% significance level.

Table 2. Average volume expansion after treatment with ozone gas at 2.5 mg L^{-1} and specific flow rates of 0.23, 0.35, and 0.73 m^3 min t^{-1}.

Treatments	Specific flow rate (m^3 min^{-1} t^{-1})		
	0.23	0.35	0.72
Control	36.33 ± 1.26	35.17 ± 1.16	35.67 ± 0.29
Ozone	35.17 ± 0.29	35.00 ± 0.50	35.50 ± 1.32

Conclusions

The specific flow rate influences the process of saturation of popcorn kernels with ozone. Ozone gas presented insecticidal potential at all specific flow rates tested, and it did not hinder the volume expansion of the popcorn kernels.

Acknowledgments

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