Assessing Ozone Treatment for Hospital Air Quality: Sustainability Study

ORAL
Ph.D. Student: N
Journal: CEJ

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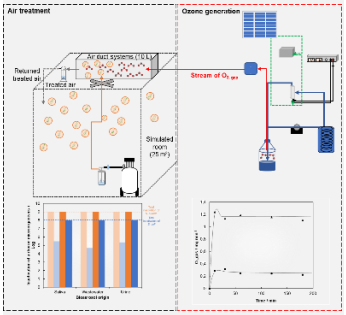

Currently, attention to airborne transmission of infectious diseases and indoor air purification in buildings has gained greater importance, especially in hospital environments due to the presence of immunosuppressed patients. High concentrations of bioaerosols present in the air of critical hospital areas, such as operating rooms, require the development of ventilation technologies that improve air quality. Among these technologies, electrochemical devices that generate oxidants in the gas phase could be a novel alternative. In this work, the complete inactivation of airborne antibiotic-resistant bacteria such as *Escherichia coli* and *Staphylococcus aureus* is achieved by applying 1.16 mg min^{-1} of electrochemically generated ozone gas. The evolution of *mec*A *blaTEM* genes is also evaluated. The effect of ozone gas on bioaerosol disinfection is studied by monitoring its effects on bacterial viability and membrane permeability. Finally, the sustainability of the technology is evaluated through a Life Cycle Assessment.

Introduction

Air quality in hospital environments is of particular concern due to the transmission of infectious diseases among immunosuppressed patients through bioaerosols. Numerous studies have reported high concentrations of bacteria and fungi in various hospital areas. For example, average bacterial and fungal concentrations of 3.95 E+2 and 1.91 E+2 CFU m^{-3}, respectively, were found in surgical areas where air quality is essential [1]. Therefore, indoor air purification technologies must be developed to improve the design of thermal installations. Among these technologies, the development of electrochemical devices can be presented as an alternative, due to their ability to generate gaseous oxidants in situ.

Ozone is a promising oxidant for indoor air purification due to its ease of production, lack of by-products, and strong antimicrobial properties. Electrochemical ozone generation via water oxidation shows potential advantages over corona discharge methods by providing high concentrations even at low voltages. Our research group has studied on optimizing operating parameters to maximize ozone production and gas-phase utilization, advancing electro-ozonizer technology beyond previous studies focused on liquid-phase performance [2].

In this context, the main objective of this work is to evaluate the technical feasibility of electrochemically generated ozone gas treatment for indoor air bioaerosols in hospitals. Additionally, a life cycle assessment (LCA) is performed using SimaPro software to describe the impact of this technology.

Material and Methods

A commercially available proton exchange membrane (PEM) cell (CONDIAPURE®, CONDIAS GmbH) is used to generate ozone. This cell has four DIACHEM® mesh electrodes with an active anodic area of 24 cm^2 separated in pairs by a Nafion® proton exchange membrane. A 0.5 mM perchloric acid solution is recirculated through the cell. The ozone gas generated from the electrolyte is extracted with a vacuum pump.

Bioaerosols are produced by nebulizing three different synthetic solutions (saliva, urine and wastewater) using a 3-jet Collison nebulizer. These solutions are previously enriched with *E. coli* ATCC 35218 and *S. aureus* ATCC 43300 with their ARGs bla_{TEM} and mec_A, respectively.

The generated ozone and bioaerosol are introduced into a 10 L duct simulating a ventilation system. The mass flow rate of ozone gas is evaluated by titration. To evaluate the inactivation of *E. coli* and *S aureus* and their ARGs, the concentration is measured by indirect impedance (CFU mL^{-1}) and real-time PCR (number of gene copies mL^{-1}), respectively.

The life cycle analysis is developed using SimaPro software for a simulated case of a hospital room of 25 m^3 with a proportional bacteria concentration to that of the experimental cases. To determine the most significant impacts discerned from this process, AWARE, USEtox and ReCiPe methods were used to quantify the environmental load at 3 Midpoints categories (water footprint, global warming potential and human toxicity). All this impact categories are normalized per m^3 of treated air (functional unit of the

study).

Results and Discussion

First, the generation of an ozone gas stream by electro-oxidation of water through a PEM cell is evaluated for two different intensities: 1 A and 3 A. The maximum generation of ozone in the electrolyte occurs during the first 30 minutes of the process, and then, the concentration of ozone is maintained at a constant value that is directly dependent on the applied intensity. Furthermore, the profile of the ozone gas that is desorbed from the electrolyte is similar to the profile of ozone generated in the liquid phase. A mass flow rate of ozone gas of 0.24 mg min^{-1} and 1.16 mg min^{-1} is obtained when 1 A and 3 A are applied, respectively.

In this study, the ozone gas stream from electro-ozonizers is valorized for the air purification in hospitals. Specifically, the inactivation of airborne antibiotic-resistant bacteria *S. aureus* ATCC 43300 and *E. coli* ATCC 35218 is evaluated after 120 minutes of continuous treatment with ozone gas. Three types of bioaerosols are tested to mimic those produced by saliva atomization when infected individuals speak, cough or sneeze, and those emitted from toilet flushes [1]. Figure 1 shows that *S. aureus* is totally inactivated (9 logs) in each case study, despite the amount of ozone gas used. However, *E. coli* is only completely inactivated (8 logs) when 1.16 mg min^{-1} of ozone gas is applied. In addition, the inactivation is also influenced by the inorganic/organic compounds present in the chemical composition of the bioaerosols due to parallel chemical reactions of ozone.

The degradation of antibiotic resistance genes is also studied to avoid the horizontal gene transfer processes: *mec*A gene from the *S. aureus* ATCC 43300 responsible for methicillin resistance, bla_{TEM} gene from *E. coli* ATCC 35218 conferring resistance to β-lactam antibiotics. The removal of both ARGs increases with increasing mass flow rate of the applied ozone gas. However, the bla_{TEM} gene is reduced to a lesser extent due to its resistance to ozone. The inactivation mechanism of ozone is followed by the effects on the membrane permeability of each target bacterium, using the crystal violet uptake technique.

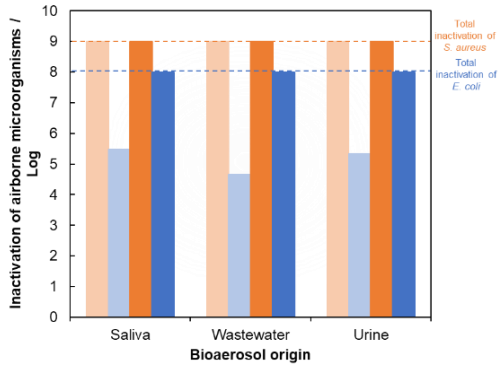

Figure 1. Log inactivation of *S. aureus* ATCC 43300 (orange color) and *E. coli* ATCC 35218 (blue color) in hospital bioaerosols resulting from continuous treatment with ozone gas after 120 minutes. Mass flow rate of ozone gas: 0.24 mig min^{-1} (light color), 1.16 mig min^{-1} (dark color).

Finally, the sustainability of the process is evaluated using the LCA methodology for three different impact categories. The treatment of *S. aureus* and *E. coli* bioaerosols with 1.16 mg min^{-1} of ozone gas could allow the recirculation of the treated air in a triple hospital room as "acceptable" (WHO) or "very low" (EC) levels. Regarding the LCA, the most relevant impacts are obtained for the carbon and water footprint being the human toxicity less significant. Thus, the treatment with 0.24 $mg_{O3}min^{-1}$ reaches an environmental impact of 64 g of CO_2 eq. and 216 L of water per m^3 of air treated. In case of the carbon footprint, major contribution is due to the energy consumption of the process which account for about 75% of the overall impact, while for water footprint the impact of the experimental set-up is responsible for more than 90%. For the inactivation of E. coli (1.16 mg_{O3} min^{-1}) the environmental impact increases by 35 % as a result of the higher energy consumption of the cell. However, this impact can be potentially reduced if renewable energies are coupled such as solar panels with a battery system.

Conclusions

Utilizing electrochemical PEM cells to produce ozone demonstrates promising efficacy in air purification for vital facilities like hospitals, particularly when integrated with duct airflow systems to prevent hospital-acquired infections. Energy consumption is a major contributor to the overall impact of the carbon footprint and human toxicity, while the impact of the experimental set-up is more relevant to the water footprint. The treatment with the highest ozone production caused an increase of the 35 % in the overall impact.

Acknowledgments

This work has been funded by the Junta de Comunidades de Castilla-La Mancha (JCCM) and the European Union (European Regional Development Fund) through the project SBPLY/21/180501/000035.

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