TRIDENT

The Science Behind AirDome™ Technology

AirDome™ Eliminates Airborne Biological Particles Faster with Greater Effectiveness

Samuel Wei Yang Lim, Sian Yang Ow, Laura Sutarlie, Yeong Yuh Lee, Ady Suwardi, Chee Kiang Ivan Tan, Wun Chet Davy Cheong, Xian Jun Loh and Xiaodi Su

INSTITUTE OF MATERIALS RESEARCH AND ENGINEERING (IMRE), AGENCY FOR SCIENCE, TECHNOLOGY AND RESEARCH (A*STAR)

IMPACT FACTOR 4.1

INDEXED IN: PubMed

CITESCORE 7.4

microorganisms

MDPI

microorganisms

MDPI

Article

Bioaerosol Inactivation by a Cold Plasma Ionizer Coupled with an Electrostatic Precipitator

Samuel Wei Yang Lim, Sian Yang Ow, Laura Sutarlie *, Yeong Yuh Lee, Ady Suwardi †, Chee Kiang Ivan Tan, Wun Chet Davy Cheong, Xian Jun Loh and Xiaodi Su *

Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), 2 Fusionopolis Way, Innovis, #08-03, Singapore 138634, Singapore; samuel_lim@imre.a-star.edu.sg (S.W.Y.L.); owsy@imre.a-star.edu.sg (S.Y.O.); leeyy@imre.a-star.edu.sg (Y.Y.L.); adysuwardi@imre.a-star.edu.sg (A.S.); ivan_tan@imre.a-star.edu.sg (C.K.I.T.); davy_cheong@imre.a-star.edu.sg (W.C.D.C.); lohxj@imre.a-star.edu.sg (X.J.L.)

* Correspondence: laura-sutarlie@imre.a-star.edu.sg (L.S.); xd-su@imre.a-star.edu.sg (X.S.)

† Current address: Department of Electronic Engineering, The Chinese University of Hong Kong, New Territories, Hong Kong SAR 999077, China; adysuwardi@cuhk.edu.hk.

Abstract: Despite best efforts in air purification, airborne infectious diseases will continue to spread due to the continuous emission of bioaerosols by the host/infected person. Hence, a shift in focus from air purification to bioaerosol inactivation is urgently needed. To explore the potential of the cold plasma technology for preventing rapid spread of airborne infectious diseases, we studied a cold plasma ionizer (CPI) device and an electrostatic precipitator (ESP)-coupled CPI (CPI-ESP) device for the inactivation and cleaning of surface-spread microorganisms and bioaerosols, using porcine respiratory coronavirus (PRCV), *Escherichia coli* (*E. coli*), and aerosolized *E. coli* as representatives. We firstly demonstrated that CPI coupled with ESP is an effective technology for inactivating virus and bacteria spread on surfaces in an in-house test chamber. We then demonstrated the efficacy of CPI-coupled ESP for the inactivation of aerosolized *E. coli* in the same chamber. Furthermore, we have demonstrated the efficiency of a CPI-ESP coupled device for the inactivation of naturally occurring airborne microbials in a few indoor settings (i.e., a living room, a discussion room, a schoolroom, and an office) to determine the treatment duration- and human activity-dependent efficacy. To understand the disinfection mechanism, we conducted a fluorescence microscopy study to reveal different degrees of *E. coli* bacteria cell membrane damage under CPI treatment.

Keywords: cold plasma ionizer; non-thermal plasma; electrostatic precipitator; porcine respiratory coronavirus; *Escherichia coli*; bioaerosols; inactivation

Citation: Lim, S.W.Y.; Ow, S.Y.; Sutarlie, L.; Lee, Y.Y.; Suwardi, A.; Tan, C.K.I.; Cheong, W.C.D.; Loh, X.J.; Su, X. Bioaerosol Inactivation by a Cold Plasma Ionizer Coupled with an Electrostatic Precipitator. *Microorganisms* **2024**, *12*, 1923. https://doi.org/10.3390/microorganisms12091923

Academic Editors: Yunping Han and Changliang Nie

Received: 24 July 2024
Revised: 11 September 2024
Accepted: 13 September 2024
Published: 21 September 2024

1. Introduction

Bioaerosol and surface transmission are the most common routes to spread infectious respiratory diseases, for instance, the SARS-CoV-2 virus [1–3]. Reducing the spread of such infectious diseases can be achieved by either reducing human exposure to bioaerosols (e.g., wearing surgical masks) or reducing the quantity of bioaerosols via inactivation/disinfection techniques.

For indoor spaces, bioaerosols can be removed by using high-efficiency particulate air filtration (HEPA filters) and electrostatic precipitators (ESPs) to adsorb bioaerosols, including mold spores, bacteria, pollen, viral particles, etc. [4–7]. HEPA filters remove particles from air that are forced through, but microorganisms are known to survive on a HEPA filter [8]. On the other hand, ESP removes particles from a gas stream by using electrical energy to confer a positive or negative charge to aerial particulates [9]. The charged particles are then attracted to collector plates carrying the opposite charge. ESP is mainly used to remove particulate matter (PM) in coal-fired power plants [10,11].

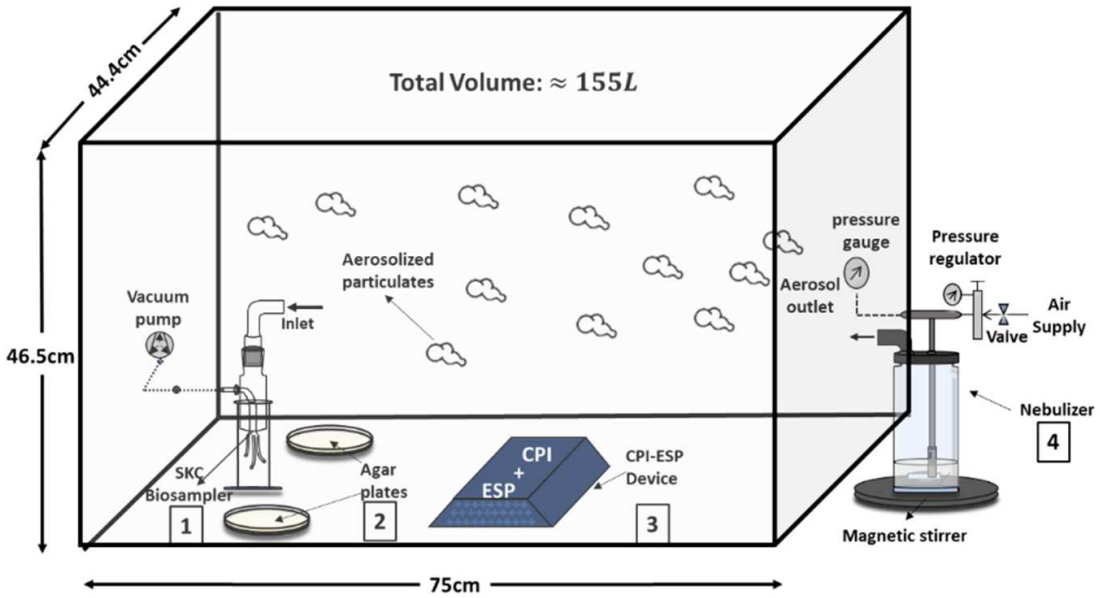

Figure 2. Schematic drawing of bioaerosol testing chamber and apparatus components. (1) SKC BioSampler for active sampling. (2) Agar plates for passive sampling. (3) CPI-ESP device. (4) Nebulizer.

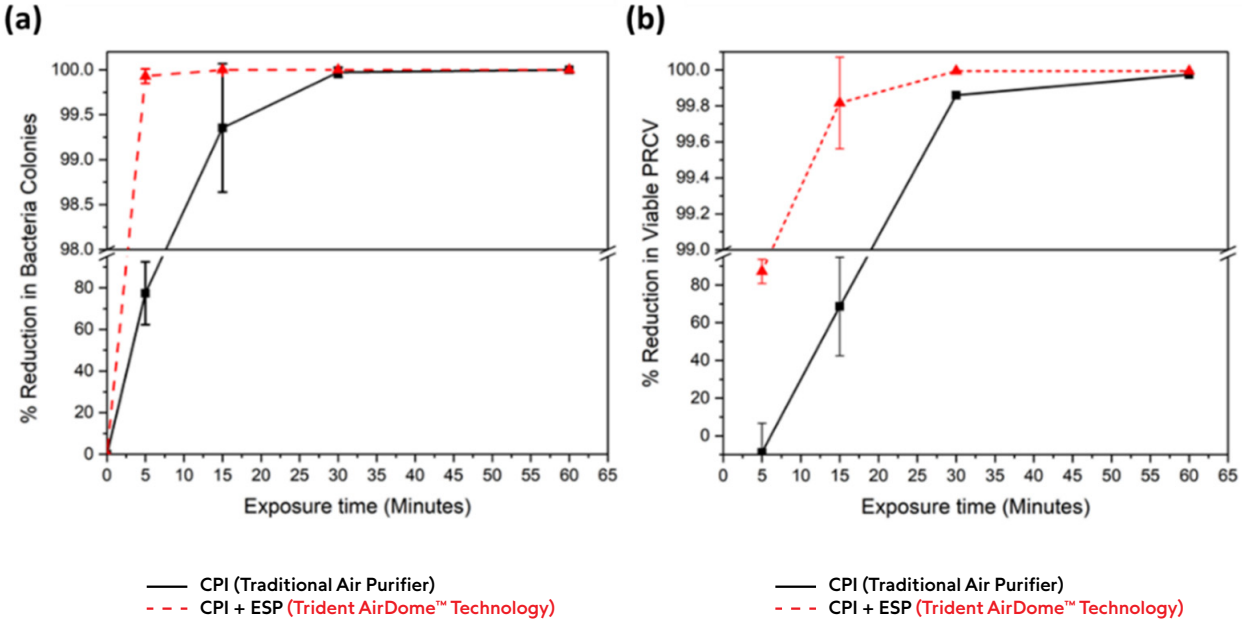

Figure 4. Percentage reductions of (**a**) *E. coli* and (**b**) PRCV in the testing chamber over time. The standard deviations at 5 min and 15 min are 6.43% and 0.25%, respectively. The standard deviations beyond 30 min remained as zero from no viable counts.

4. Conclusions

We have investigated the efficiency of a CPI device and an ESP-coupled CPI device (CPI-ESP) for bioaerosol inactivation. Through controlled experiments in a bioaerosol chamber, we have demonstrated that the CPI-ESP combination is more effective in the inactivation of the virus and bacteria (both aerosolized in air and spread on surfaces) than CPI alone; and the reduction in the aerosolized viable microorganism (*E. coli*) by the CPI-ESP device is faster than the reduction in the surface-spread microorganism. We have also exploited a commercial air purifier that consists of CPI and ESP to study the bioaerosol inactivation in indoor settings to demonstrate the ability of this machine in inactivating naturally occurring environmental microorganisms, in treatment time- and space volume-dependent manners. Using the fluorescence microscopic technique, we have revealed the inactivation mechanism that involves the perforation of the bacterial cell membrane. We believe that this work can enhance the understanding of the mechanism of bioaerosol inactivation by CPI-ESP and provide guidance for the future optimization and practical use of these combined technologies. Further studies can be performed to understand the effect of various environmental conditions (humidity, temperature, etc.) on the inactivation efficiency for a given CPI-ESP device, or the impacts of device specifications on inactivation efficiency.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/microorganisms12091923/s1, Table S1: Specification of the CPI-ESP devices; Figure S1: Characterization of Aerosolized *E. coli*; Figure S2: Plate culture mapping of aerosolized *E. coli* in the chamber; Figures S3 and S4: Bacteria count of aerosolized *E. coli* collected by active sampler (SKC BioSampler) and passive sampler (Agar plate); Figures S5–S7: Fluorescence microscopy of *E. coli* collected by SKC BioSampler with CPI treatment duration of 0-, 5-, 15-min, respectively; Figure S8: Ozone data obtained in the meeting room without and with CPI-ESP treatment.

Author Contributions: S.W.Y.L.: Conceptualization, Methodology, Data curation, Investigation, Writing—Original draft preparation and drawing. S.Y.O.: Conceptualization, Methodology, Data curation, Investigation, Writing—Original draft preparation. L.S.: Conceptualization, Data curation, Investigation, Writing—Reviewing and editing. Y.Y.L.: Data curation, Investigation, Writing—Reviewing and editing. A.S.: Conceptualization, Supervision, Methodology, Writing—Reviewing and editing. C.K.I.T.: Conceptualization, Supervision, Writing—Reviewing and editing. W.C.D.C.: Supervision, Conceptualization, Writing—Reviewing and editing. X.S.: Funding acquisition, Supervision, Project administration, Writing—Reviewing and editing. X.J.L.: Conceptualization, Supervision, Writing—Reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This project was supported by the Ministry of Health (MOH) and National Centre for Infectious Diseases (NCID), Singapore under the Programme for Research in Epidemic Preparedness and Response [PREPARE-CS1-2022-003].

Data Availability Statement: The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.