Development of an Antiviral Electrostatic Precipitator to Prevent Airborne Transmission within Indoor Air Environments by Dry-aerosol Antiviral Coating Method

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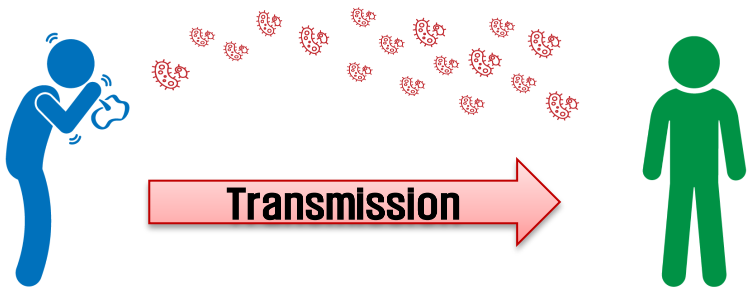
KIMM KOREA INSTITUTE OF MACHINERY & MATERIALS

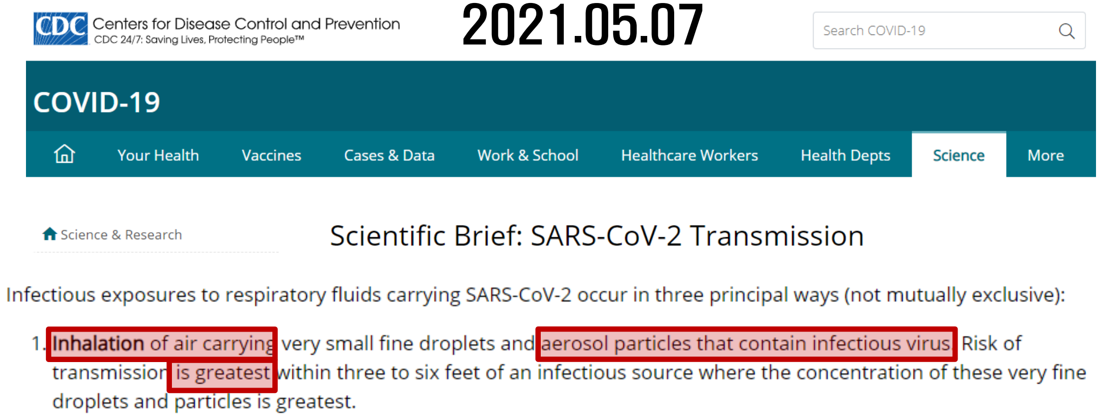
Introduction : Bioaerosols

Biological pathogens can be **transmitted by aerosols from person to person**, leading to **outbreaks**

COVID-19 Crisis



2021.05.07



➔ **COVID-19 transmission by bioaerosols**

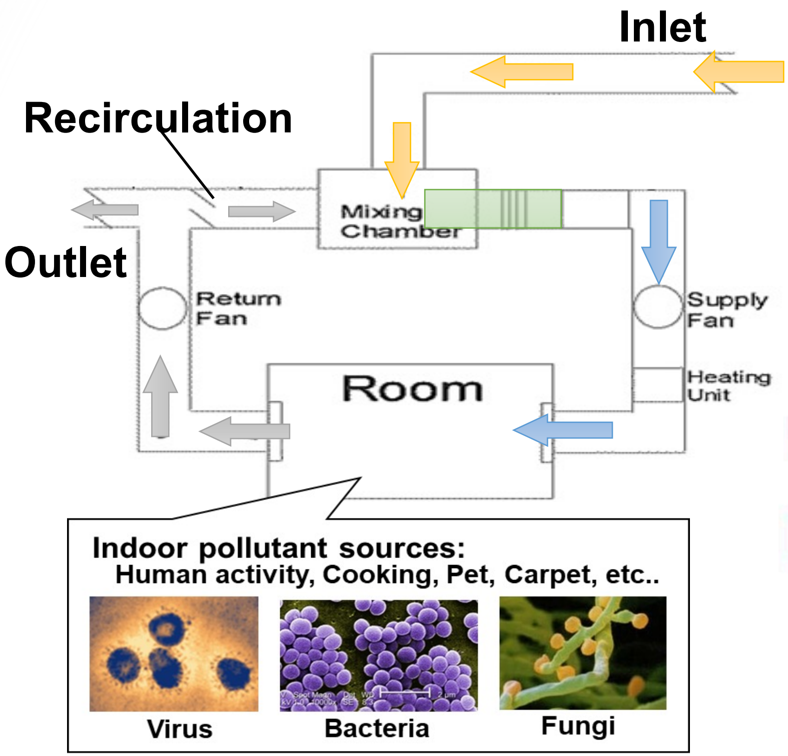
Aerosol
airborne particles

Air quality control via thermo-fluid aerosol engineering is required for prevention of COVID-19 transmission.

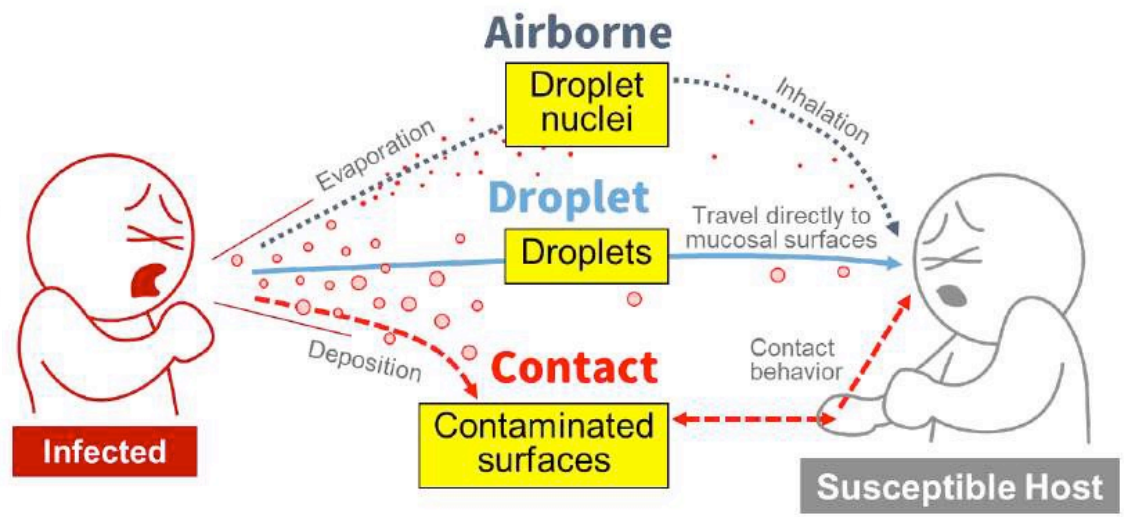
Bioaerosol
airborne particles with biological origins
such as **virus, bacteria, fungi** (molds), endotoxins, mycotoxins, spores, pollen, allergens
and other animal or plant-based matters.

Active
Airborne
Virus
Control

Introduction : Indoor air quality



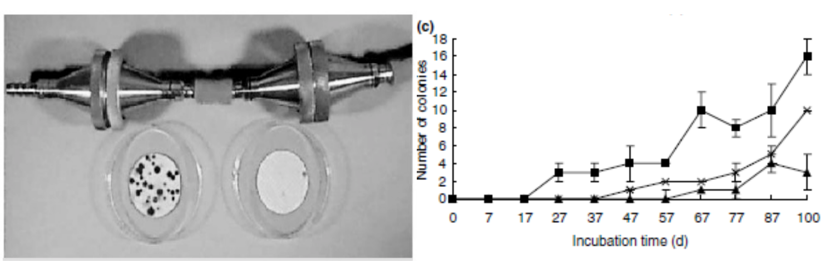
Transmissions in indoor air



from leaflet of the Office of the Prime Minister and the Ministry of Health, Labor and Welfare of Japan (2020)

Air filters for indoor air quality

Verdenelli, *et al. Journal of Applied Microbiology* (2003)



Biologically contaminated filter

➔ Microbial growth
➔ Microbial volatile organic compounds (MVOCs)

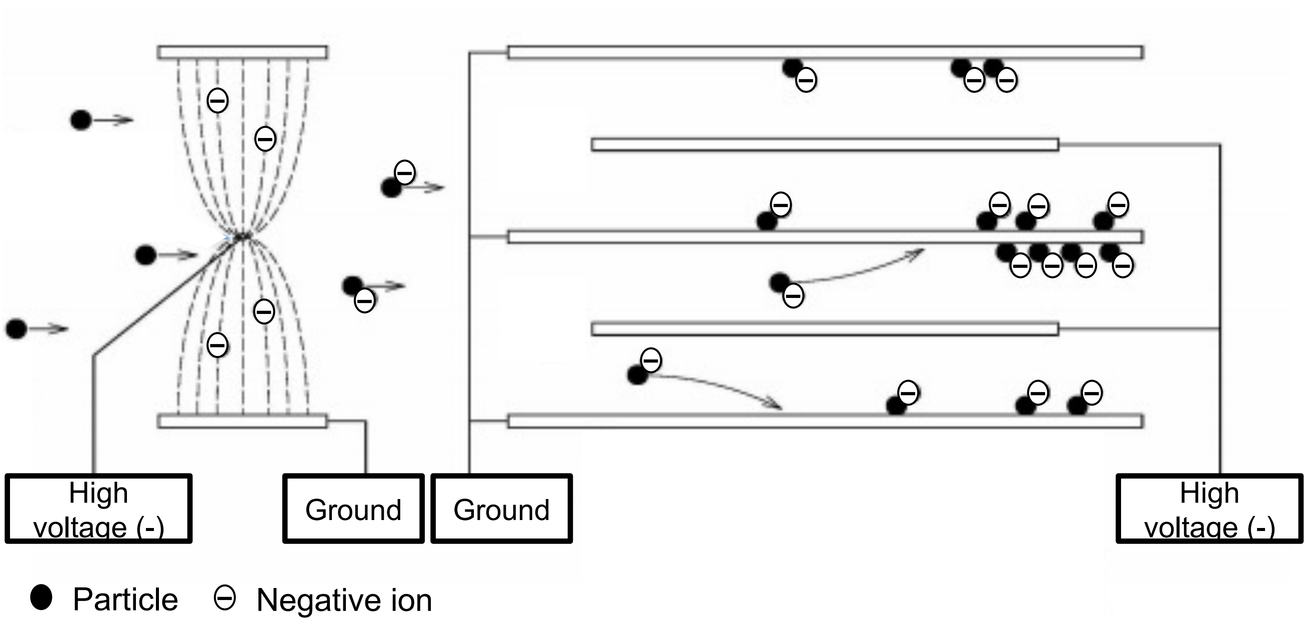
- Efficient indoor air quality (IAQ) management by filters
- Filter replacement & Energy consumption cost
- Biologically contaminated filter → transmission, odor

➡ **An alternative IAQ management technology is required for bioaerosol removal**

Background

✓ **Two-stage electrostatic precipitator (ESP)**

[1-Stage] Charging part **[2-Stage] Collection part**



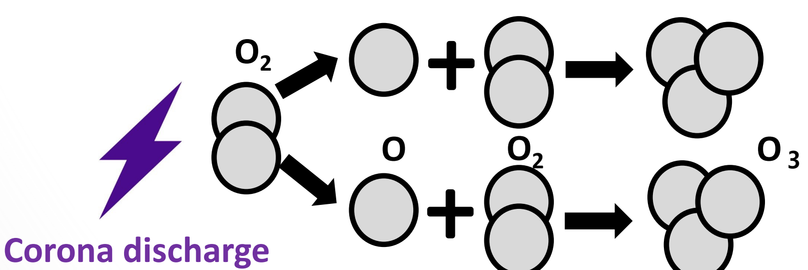
Advantage

- **Low** pressure drop
- **High** collection efficiency
- **Semi-permanent** use

Challenge

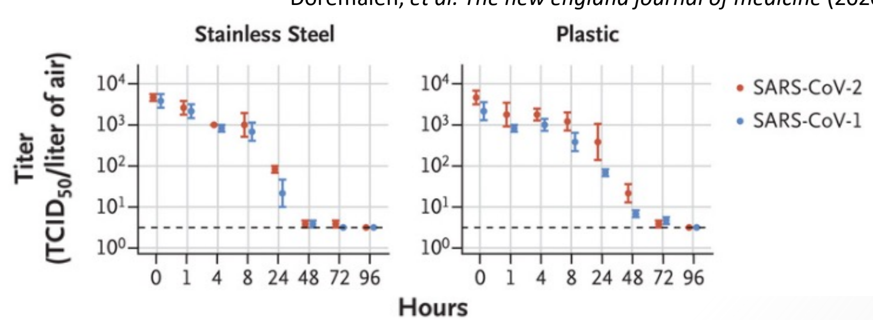
- **Ozone** generation
- **No functional** effect (such as **antiviral effect**)

✓ **Ozone generation from ESP**



✓ **Biological contamination of collection plate**

Doremalen, *et al. The new england journal of medicine* (2020)

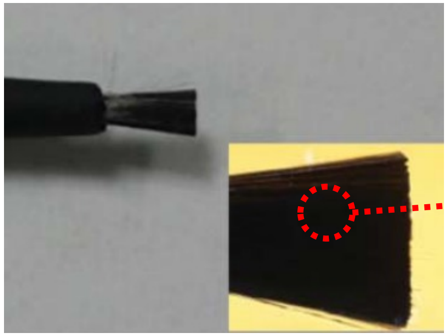


Objectives

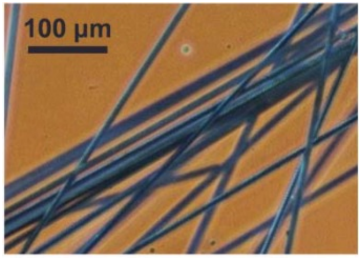
✓ **Previous research**

Carbon brush ionizer

Kim *et al.* (2011), *Aerosol Sci. Tech.*

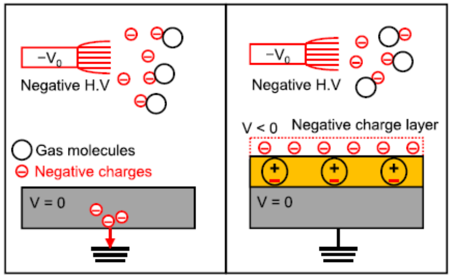


Diameter ≈ 7 µm

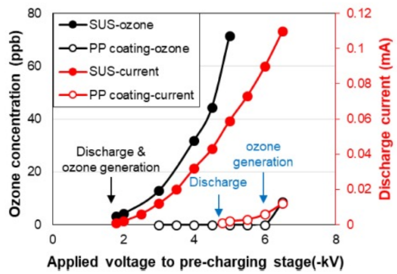


Lee *et al.* (2022), *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*

Ground plastic coating



uncoated PP coated



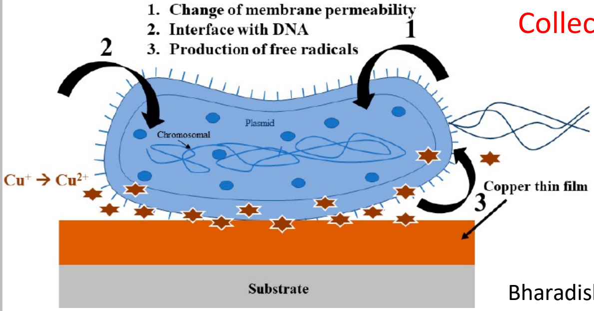
Antiviral coating

Elevator switch

Touch screen

Antiviral film

Collection plate coating



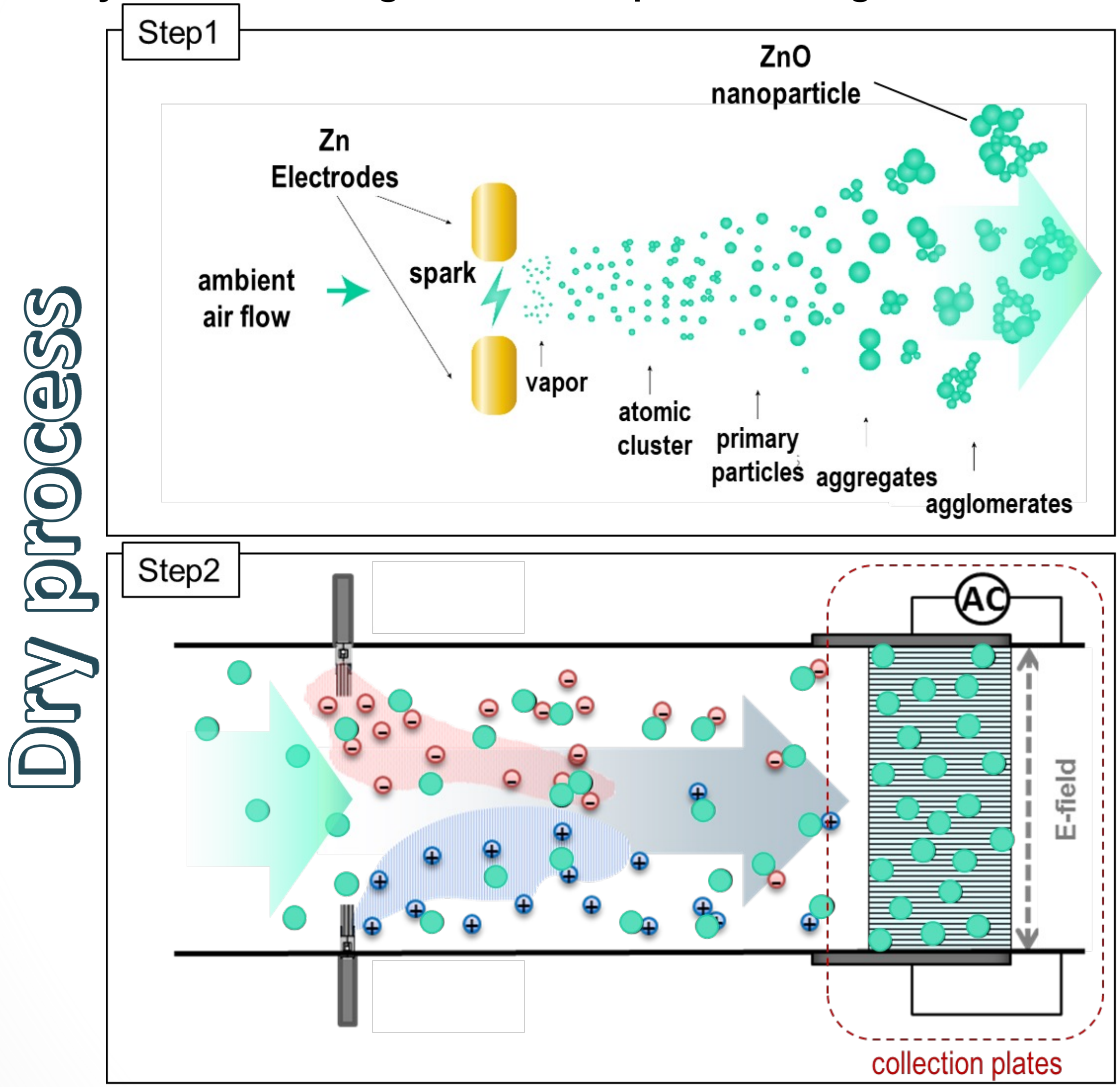
Bharadishettar *et al.* (2021), *Metals*

Objectives of the present research

- Investigation of a two-stage ESP generating near-zero ozone for the application to IAQ management
- Development of an antiviral ESP by dry-aerosol coating method for bioaerosol removal
- Performance evaluation of the ESP against aerosolized viruses
- Development of the air handling unit in the building indoor air conditioning system to confirm the industry-applicability

Experimental methods

✓ **Dry-aerosol coating method via spark discharge**



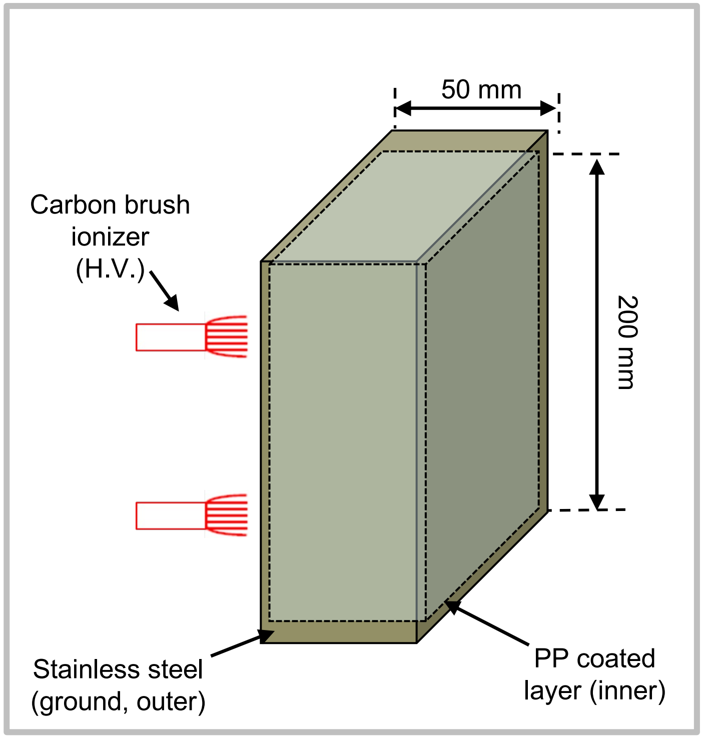
- ZnO nanoaerosols by spark discharge system as antiviral materials were generated and coated on the collection plates of the ESP.
- Bipolar charged ZnO nanoparticles via spark process, were electrostatically coated on the surface of collection plates with AC electric field.
- The uniformity of the surface treatment was evaluated by a field emission scanning electron microscope with energy dispersive X-ray spectroscopy (FESEM-EDX)

➔ Dry-aerosol coating method has scalable and realizable potential uses to manufacture the antimicrobial surfaces

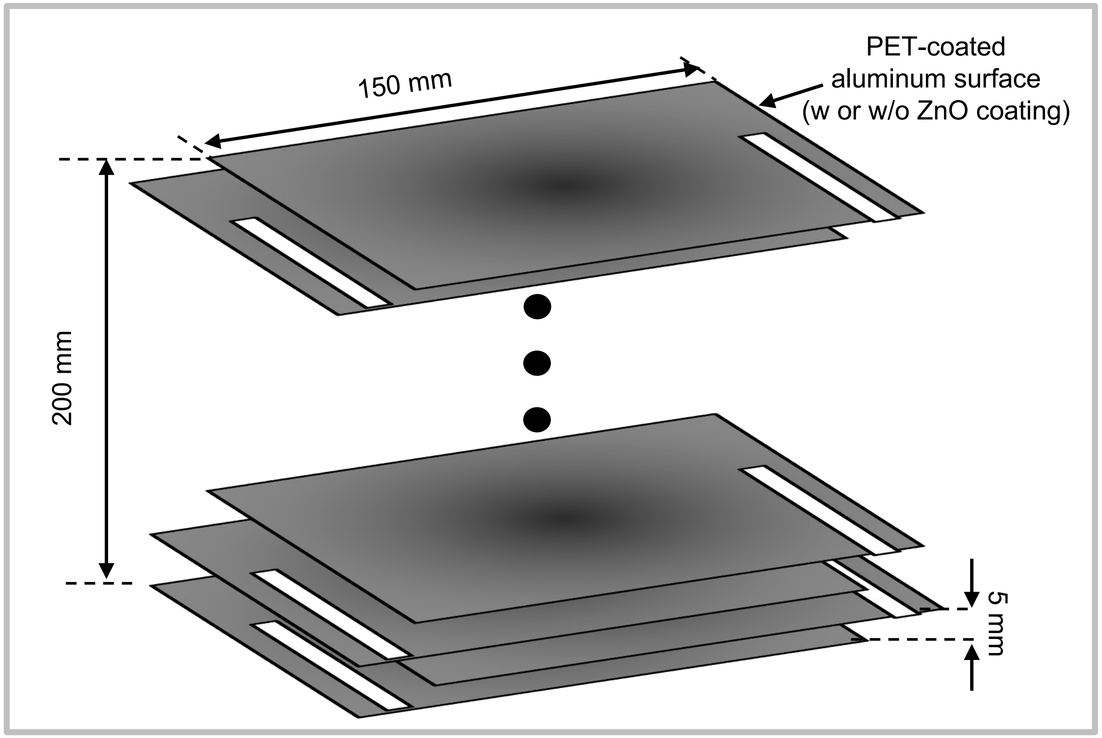
Experimental methods

✓ **Specification of the ESP**

<Charging part>



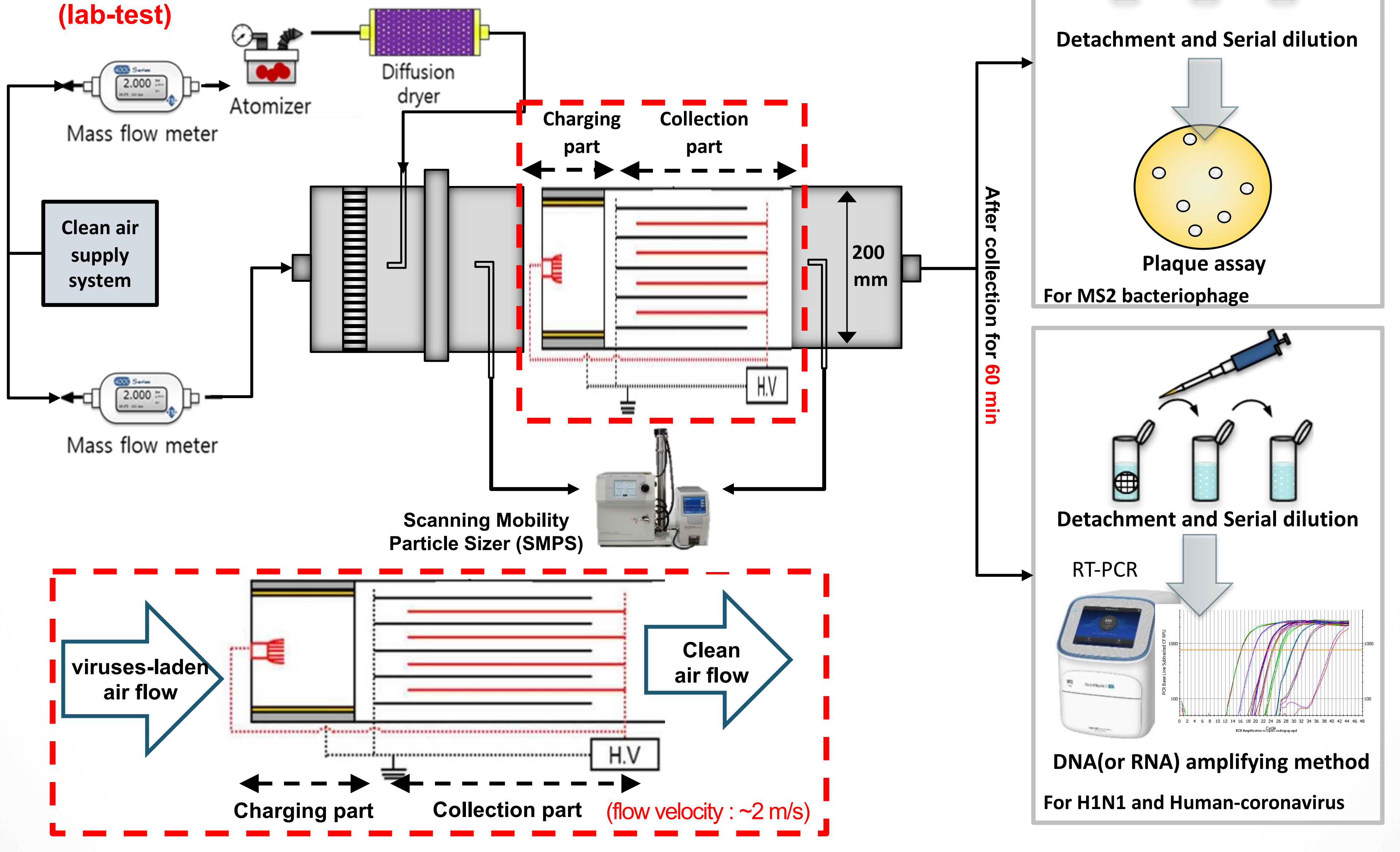
<Collection part>



- Charging part consisted of carbon brush ionizer (H.V.) & polypropylene coated layer (ground) to minimize ozone generation.
- Collection part consisted of PET-coated aluminum surfaces which were used for both the collection plate and ground electrodes to achieve its flexibility and light-weight as the collection plates
- Collection plates were coated with ZnO NPs via dry-aerosol coating method for inactivation of the collected pathogens

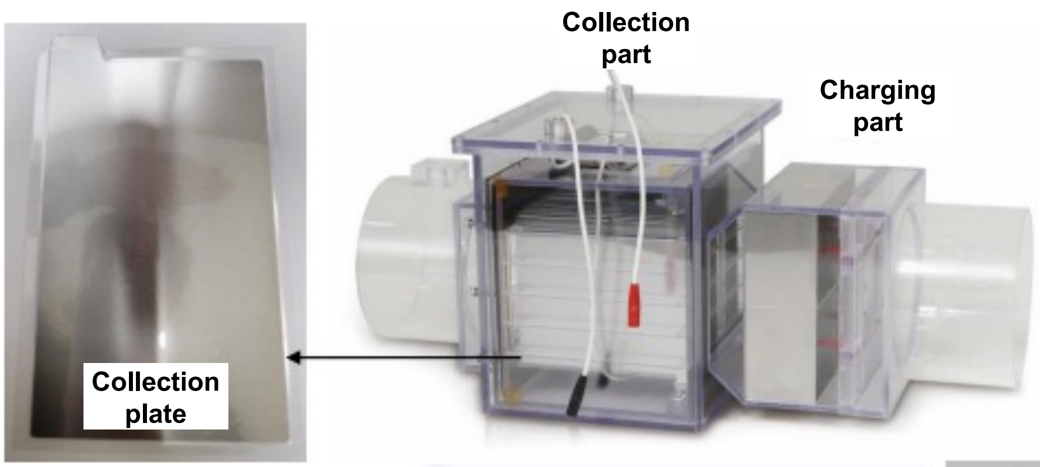
Experimental methods

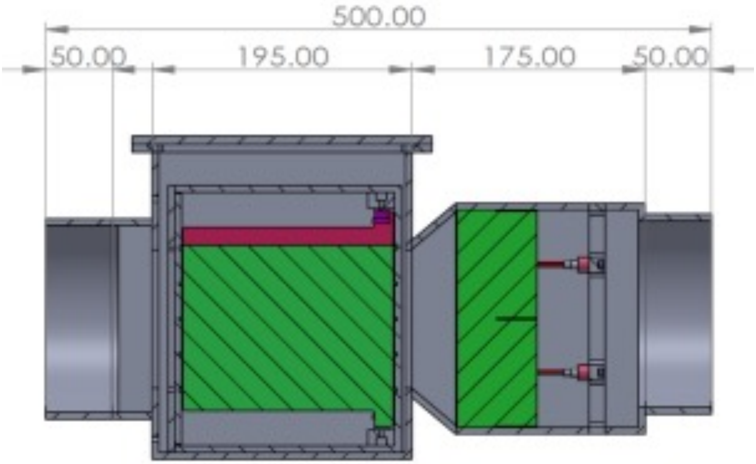
✓ **Removal and antiviral efficiencies of the ESP against aerosolized viruses (lab-test)**

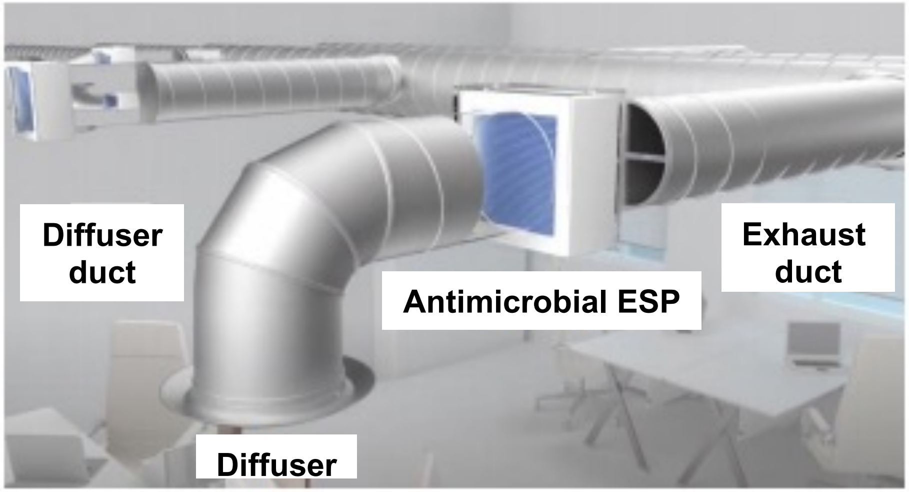


Experimental methods

✓ **Design of air handling unit in the building indoor air conditioning system**



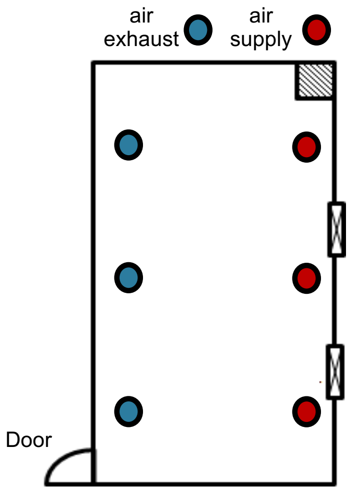


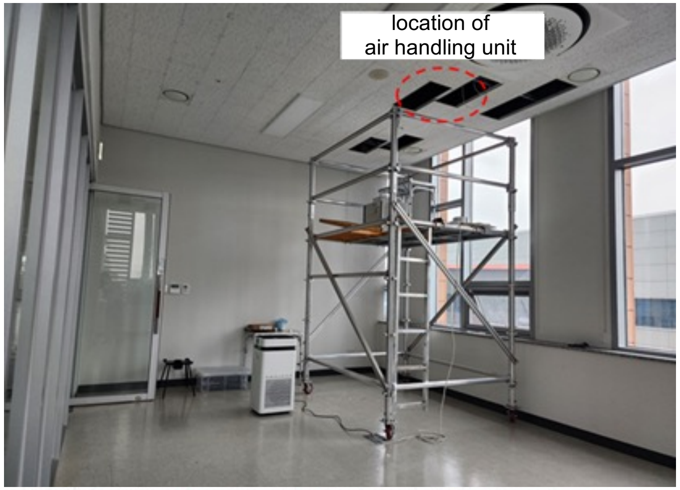


➘ We newly designed an air handling unit with the developed ESP, which is commonly acceptable in building indoor air conditioning system.

Experimental methods

✓ **Air handling unit of a building office (actual test)**

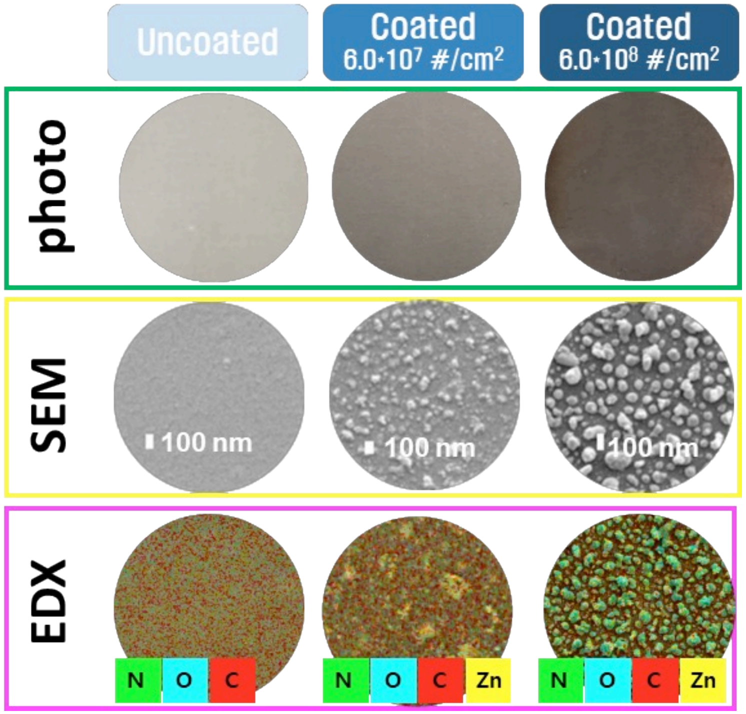




- We applied the air handling unit with antiviral ESP system on the air supply of ceiling based air conditioning system in a real building office.
- Actual test was carried out for removal of airborne pathogens generated artificially under actual building air conditioning conditions. (flow velocity : ~2 m/s)
- The antimicrobial ability of the air handling unit was evaluated.
- After actual test, it is being evaluated with a long-term test for six months to confirm the industry-applicability. (undergoing)

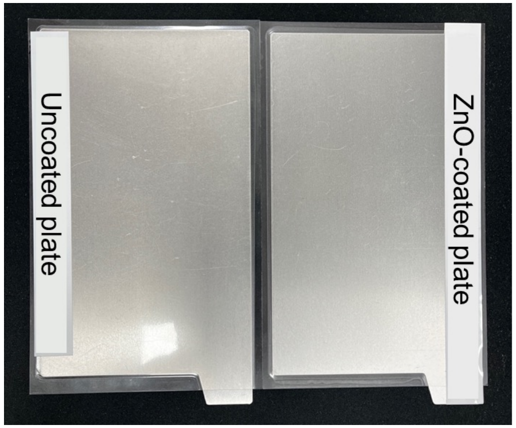
Results

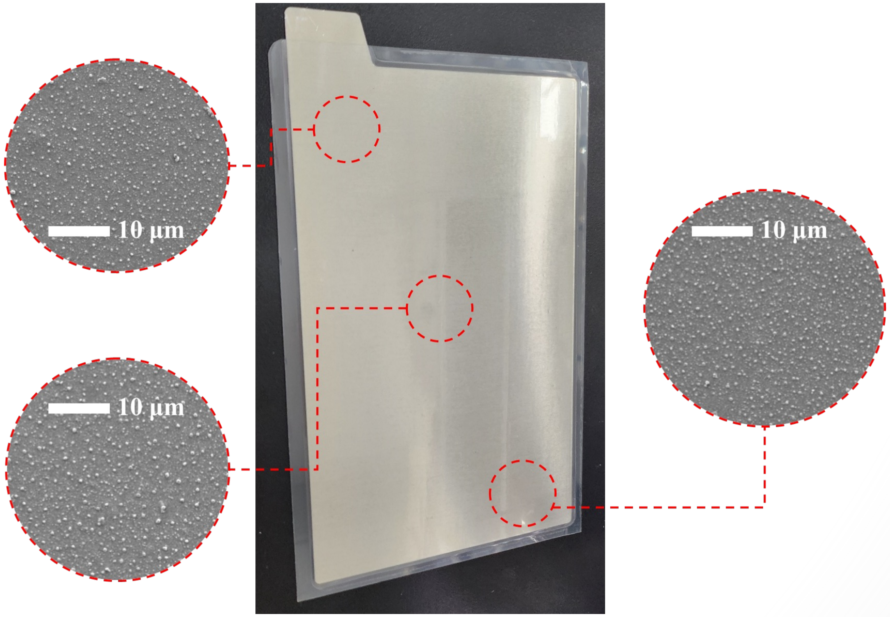
✓ **Surface with aerosol-coating areal densities**



- SEM and EDX results showed that Zn components increased with increasing coating areal densities.
- We selected the optimal ZnO coating areal density of 6.0×10^7 particles cm^{-2}.
- The suggested dry-aerosol process could achieve the high coating uniformity on the treated surfaces.

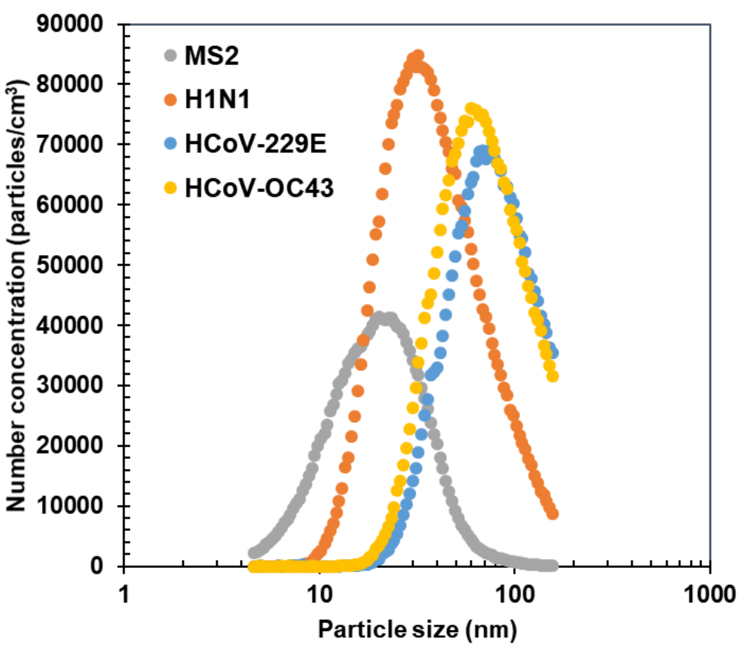
✓ **Collection plate of the antiviral ESP**



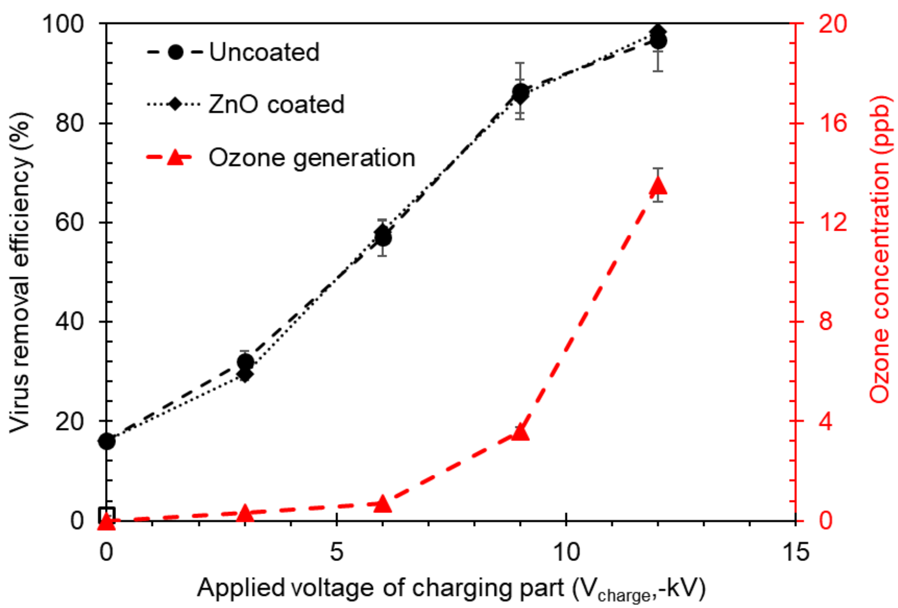


Results

✓ **Size distribution of virus particles**



✓ **Collection efficiency of the ESP**



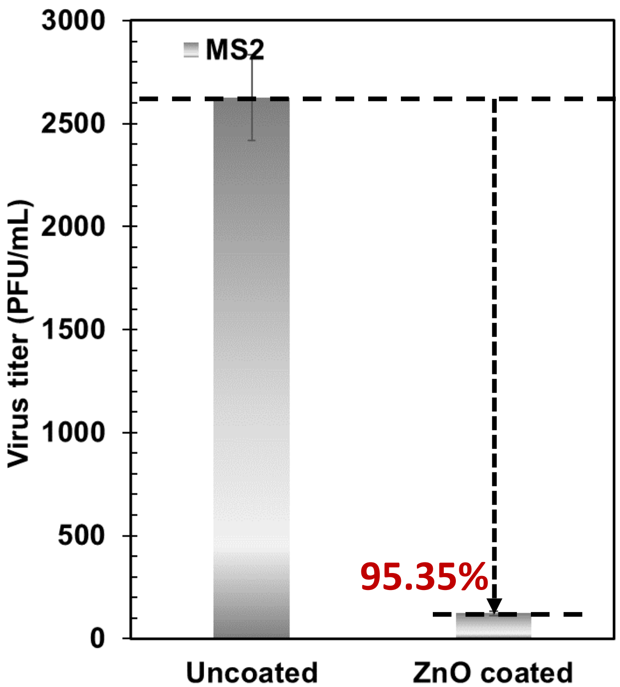
MS2 virus, $V_{collect}$: -12 kV, U_{face}: 2 m/s, RH: 35%

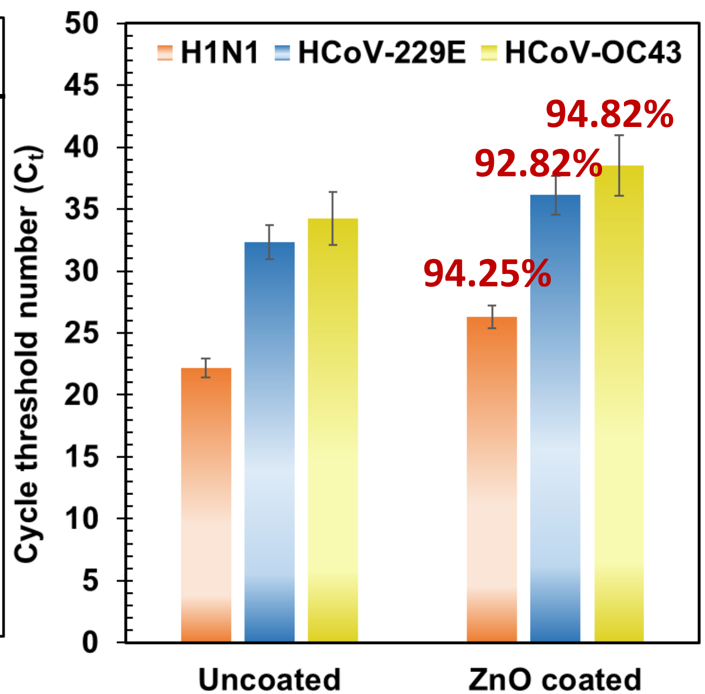
- The mode diameters of aerosolized MS2, H1N1, HCoV-229E, and -OC43 were approximately 20.2, 32.2, 73.7, and 59.4 nm, respectively.
- The collection efficiencies increased with increasing the voltage of charging part. and the ozone concentration was only 13.5 ppb when virus collection efficiency was higher than 95 %.
- No significant differences in collection efficiency were observed between uncoated and ZnO-coated collection plates.

Results

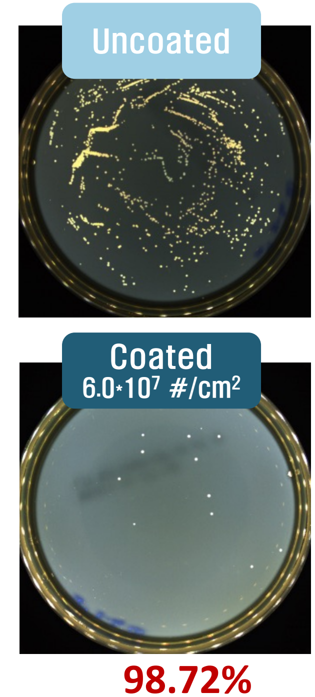
Inactivation efficiencies against aerosolized viruses (Lab-test)

V_{charge}: -9kV, $V_{collect}$: -12kV, U_{face}:2m/s





Air handling unit (Actual test)

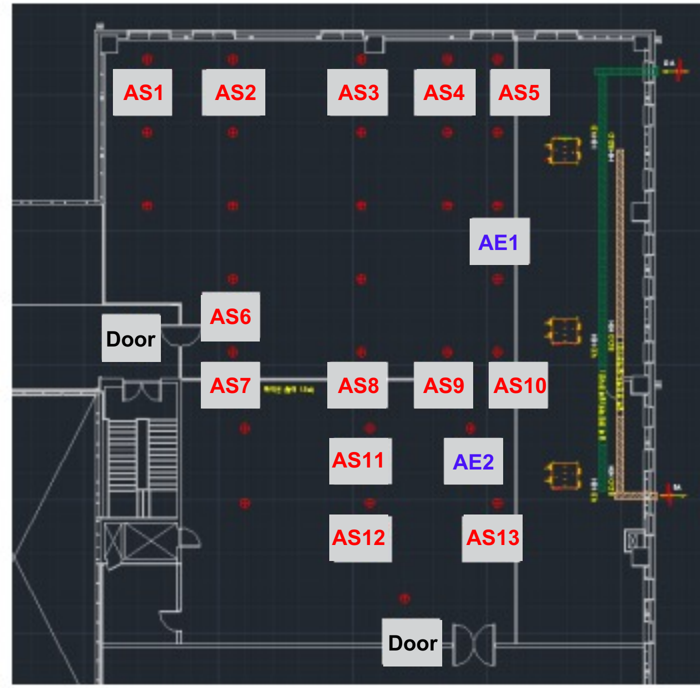


- The total inactivation efficiencies were approximately 95.4%, 94.3%, 92.8%, and 94.8% against MS2 bacteriophage, H1N1, HCoV-229E and -OC43, respectively (lab-test).
- On the air supply of ceiling based air conditioning system in a real building office, the total inactivation efficiency was approximately 98.7%, indicating that the results under the actual condition of air handling unit in the building industry were well-matched with the lab-test.

Future works

✓ **Long-term test of air handling unit**

- To demonstrate that our system has the potential to prevent airborne transmission within indoor air environments, the air handling units were installed in the building air conditioning system. The representative 15 spots were selected.
- Further investigations about reusability and durability with a long-term test for six months are undergoing to confirm the industry-applicability.



Air supply 1	Air supply 2	Air supply 3	Air supply 4	Air supply 5
				
Air supply 6	Air supply 7	Air supply 8	Air supply 9	Air supply 10
				
Air supply 11	Air supply 12	Air supply 13	Air exhaust 1	Air exhaust 2
				

Future works

✓ **Long-term test of air handling unit**

<During installation>

<After installation>

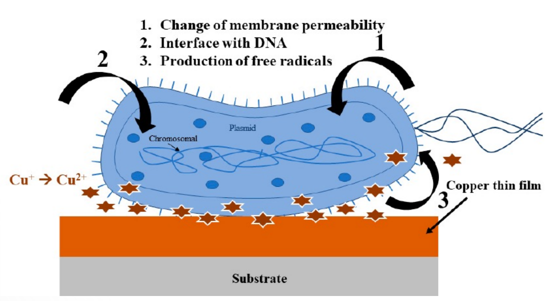
- We are monitoring the indoor air quality including concentration of PM 10 and PM 2.5, under the operation of air handling unit for six months (from this April).
- The durability of coating surface, concentrations of airborne pathogens would also be evaluated.

Conclusion

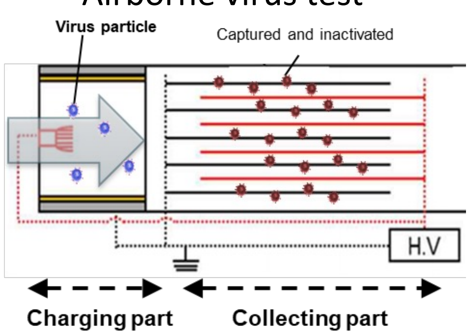
Summary

- A two-stage ESP for airborne viruses removal with high collection efficiency and near-zero ozone generation was developed as a IAQ management technology.
- To develop a antiviral ESP, ZnO NPs were coated on the collection plates via dry-aerosol coating method.
- The results showed the antiviral surfaces of the collection plates have high-coating uniformity and significant effect on reduction of infectivity of the bioaerosols without any significant differences in collection efficiency.
- Resultantly, we newly developed the antiviral ESP system on air handling unit in the building air conditioning system, which has potential to prevent airborne transmission within indoor air environments.
- Further investigations about reusability and durability with a long-term test for six months are undergoing to confirm the industry-applicability.

Collection plate aerosol coating



Airborne virus test



Antiviral air handling unit

Thank you

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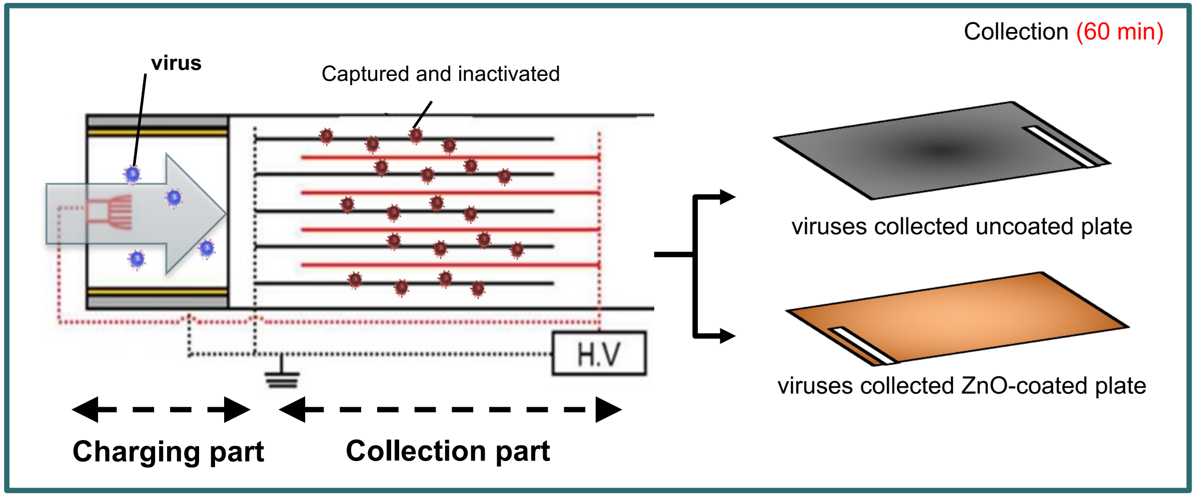
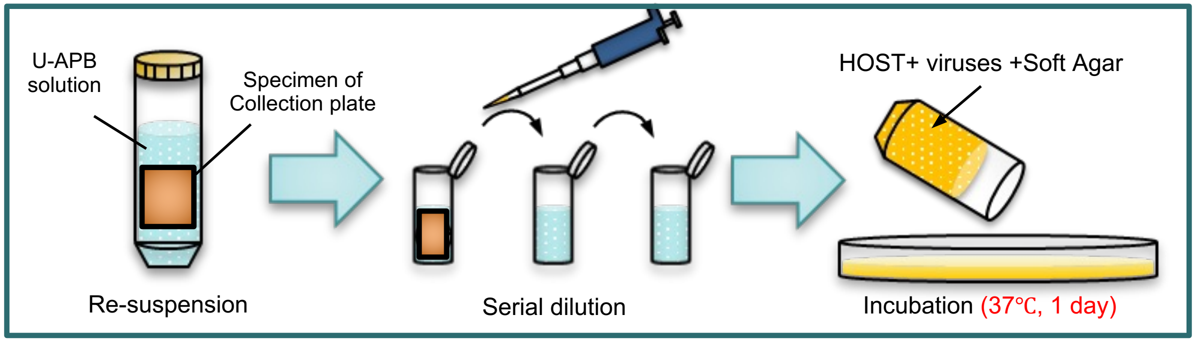
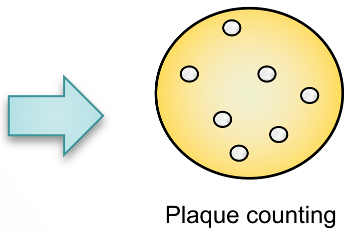
Experimental methods

✓ **Antimicrobial effect of the ESP**







$$\eta_{anti} = 1 - \frac{PFU_{ZnO\ coated}}{PFU_{uncoated}}$$

* η_{anti} : Antiviral efficiency
* $PFU_{ZnO\,coated}$: virus plaque number from ZnO coated plate
* $PFU_{uncoated}$: virus plaque number from uncoated plate

- The antiviral ability of the developed ESP was evaluated against bioaerosols
- Four kinds of viruses were selected as test bioaerosols, MS2 bacteriophage, H1N1, HCoV-229E and HCoV-OC43 as surrogates for human and animal respiratory viruses

① The viruses were collected on a collection plate of ESP for 60 mins.

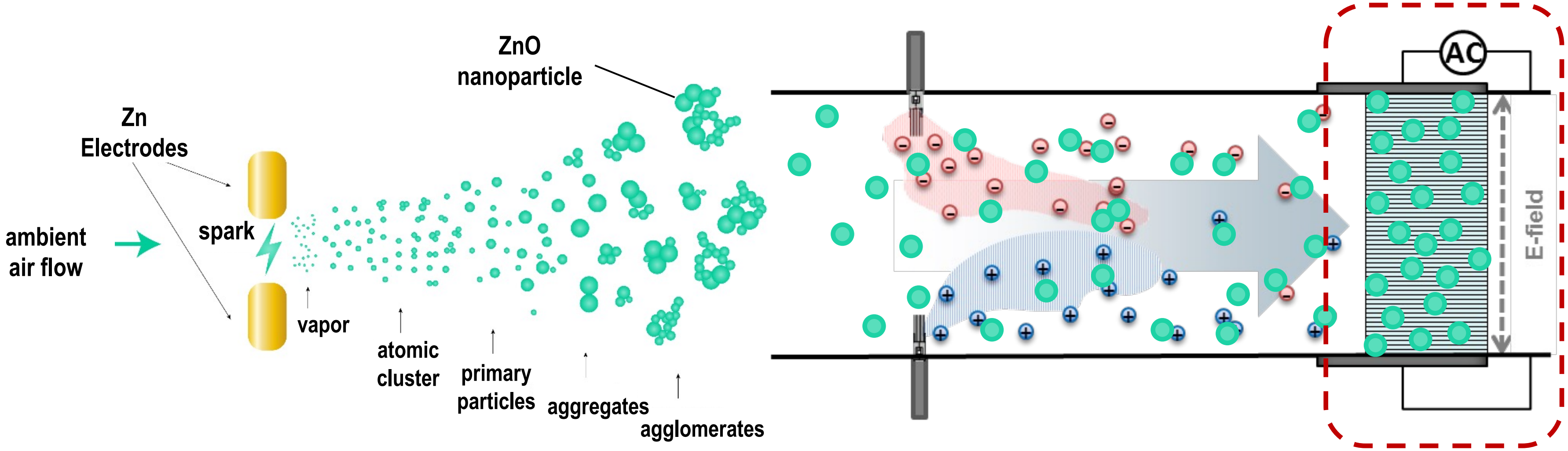
② The elution process for pathogen particles from the plate sample.

③ The eluted viruses in the solution were incubated via single agar layer method.

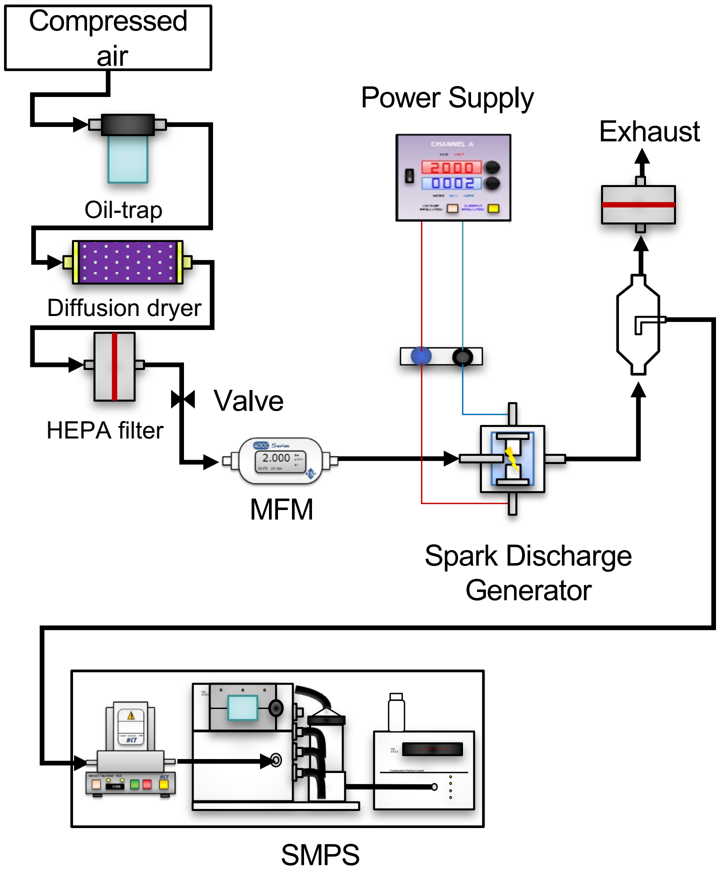
④ The concentrations of viruses and the antiviral efficiencies were calculated .

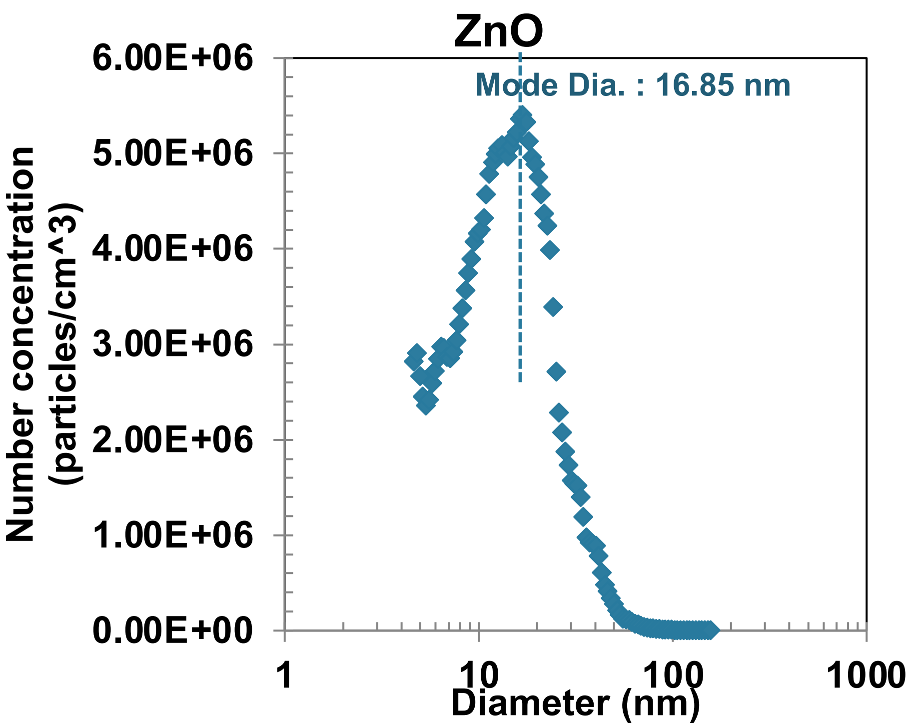
❖ Synthesis method of antimicrobial nanomaterial

- **Metallic nanomaterials : Several of them have been widely used as antimicrobial agent [1]**
  (Ex: Ag, Ag_2O, TiO_2, Si, Cu, CuO, ZnO, Au, CaO, MgO)



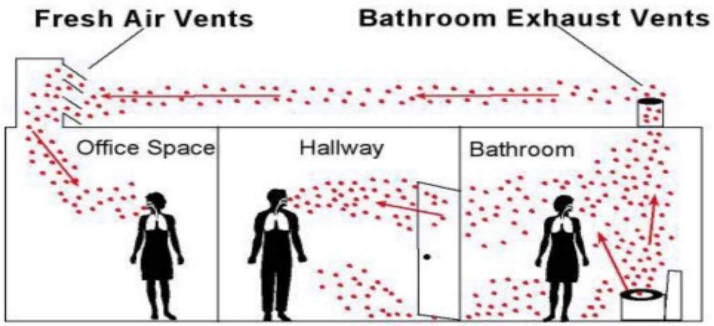
[1] Dizaj, et al. *Materials Science and Engineering: C*, 2014, 44: 278-284.


Compressed air
Power Supply
Exhaust
Oil-trap
Diffusion dryer
HEPA filter
Valve
MFM
Spark Discharge Generator
SMPS


ZnO
Mode Dia. : 16.85 nm
Number concentration (particles/cm^3)
6.00E+06
5.00E+06
4.00E+06
3.00E+06
2.00E+06
1.00E+06
0.00E+00
1
10
100
1000
Diameter (nm)

❖ Infection Routes

- **Airborne infection:**
  One that is contracted by inhalation of microorganisms or spores suspended in air on water droplets or dust particles
- **Droplet infection:**
  Infection due to inhalation of respiratory pathogens suspended on liquid particles exhaled by someone already infected
- **Contact infection:**
  Direct physical contact (body surface to body surface) between infected or colonized individual and susceptible host

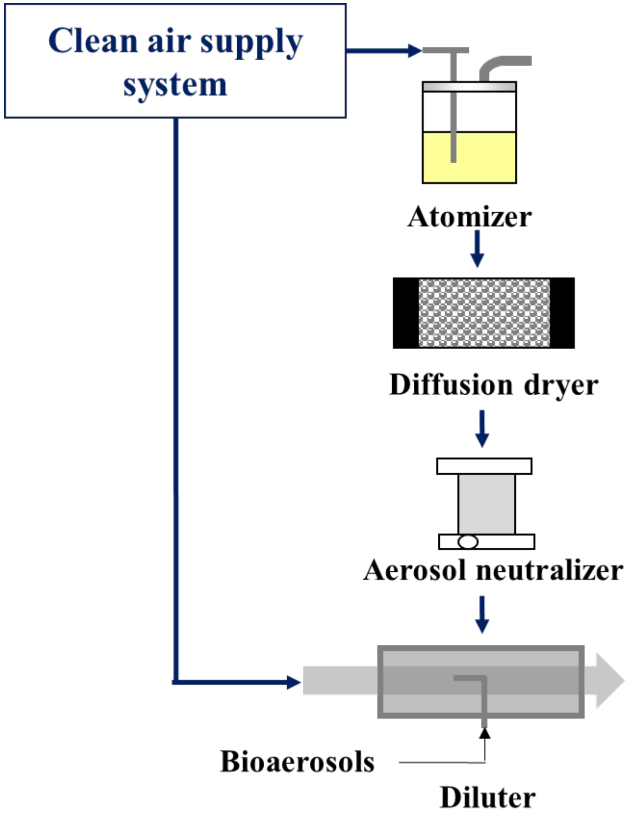


"The viruses can remain suspended in the air long enough to be dispersed"

"viruses can exist in the air of hospital rooms and also in human breath"

"Large scale outbreaks of SARS were caused via airborne exposure routes"

❖ Bioaerosol generation



1. **Bioaerosols were generated** from a Collison –type atomizer(TSI model 9302). Air flow rate was maintained at 2 lpm. .

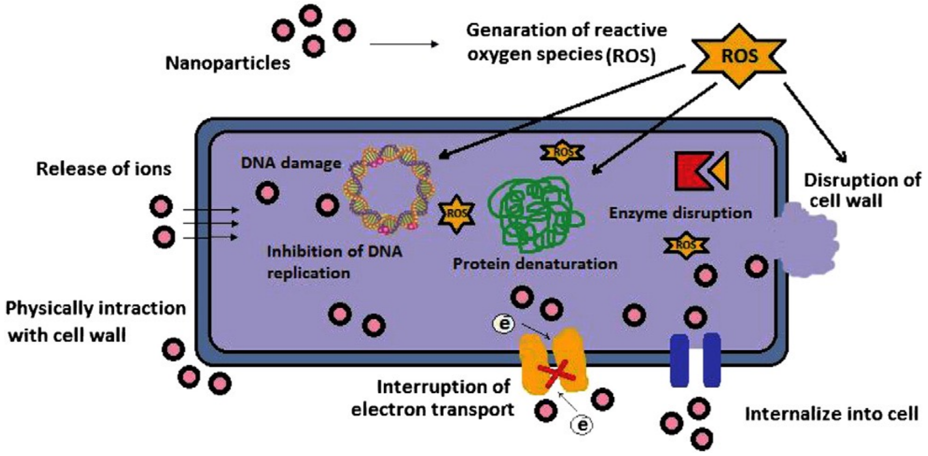
2. The bioaerosols passed through a diffusion dryer to **remove moisture**.

3. The bioaerosols passed through an aerosol neutralizer to **be electrically neutralized**.

4. The bioaerosols were **diluted** by clean air in the diluter. (dilution ratio: 12.5 - 50)

Antimicrobial mechanism

❖ Antibacterial mechanism of Metallic nanomaterial



- Interaction with P or S compounds of cell surface.
- Generation metallic ion which can easily interact with cystein, guanine or thiol (-SH)group of the enzymes.
- Generation ROS such as superoxide ($^{\bullet}O_2^-$), hydrogen peroxide (H_2O_2), and highly toxic hydroxyl radical ($^{\bullet}OH$)
- Interaction with K^+ or Ca^+

Antimicrobial mechanism

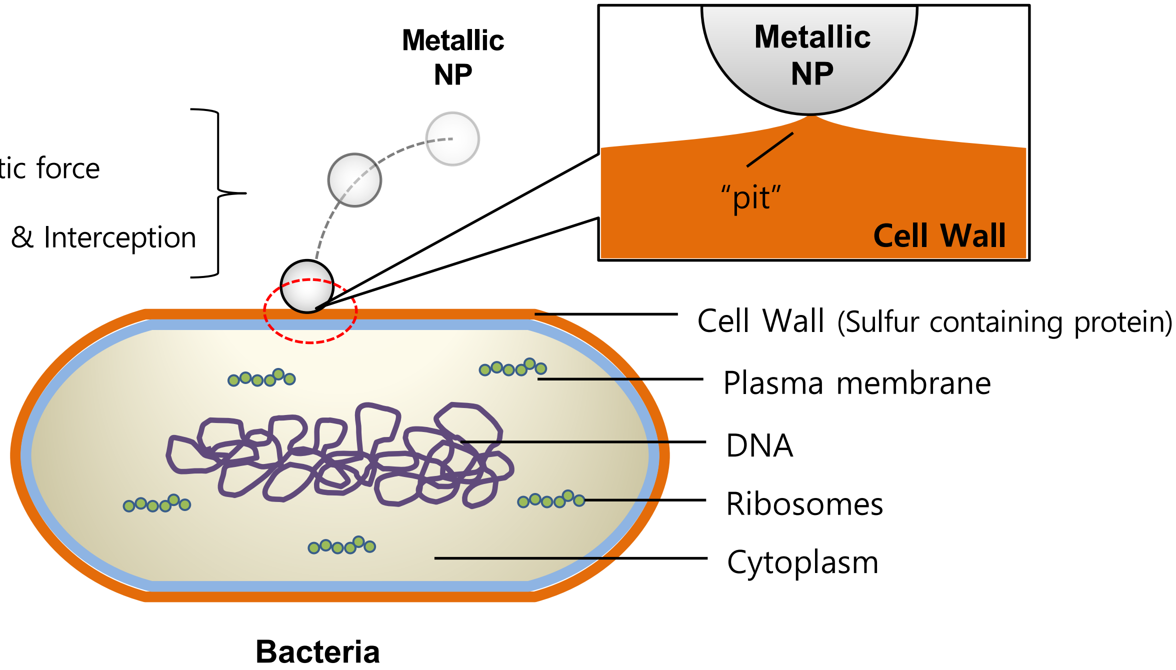
❖ Antiviral mechanism of Metallic nanomaterial

- lysing viral membranes on contact or by binding to virus coat proteins
- Nanoparticles bind with a viral envelope glycoprotein and inhibit the virus by binding to the disulfide bond regions of the CD4 binding domain within the HIV-1 viral envelope glycoprotein gp120.
- Interact with the hepatitis B virus (HBV) DNA and extracellular virions with its different size, and could inhibit the production of HBV RNA and extracellular virions.
- Denaturing enzymes by reactions with sulfhydra, amino, carboxyl, phosphate, and imidazole groups.

Antimicrobial mechanisms via metallic NPs

❖ **Attachment [1]**

- Electrostatic force
- Diffusion
- Impaction & Interception

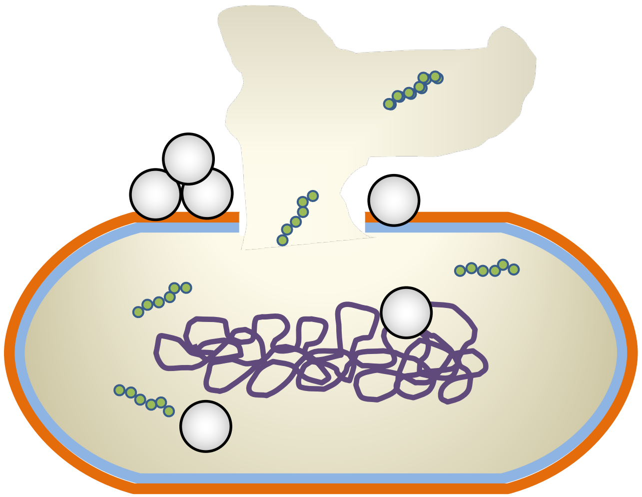


- Metallic NPs incorporated into the bacteria membrane, thus inducing a formation of pits.

[1] Lemire, et al. Antimicrobial activity of metals: mechanisms, molecular targets and applications, *Nature Reviews Microbiology*, 2013, 11: 371-384.

Antimicrobial mechanisms via metallic NPs

❖ **Attachment [1]**

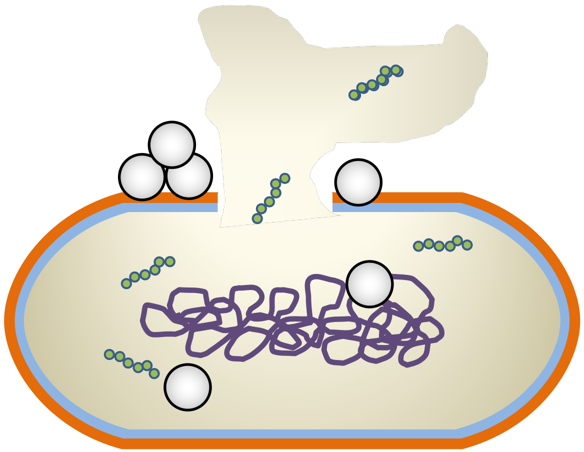


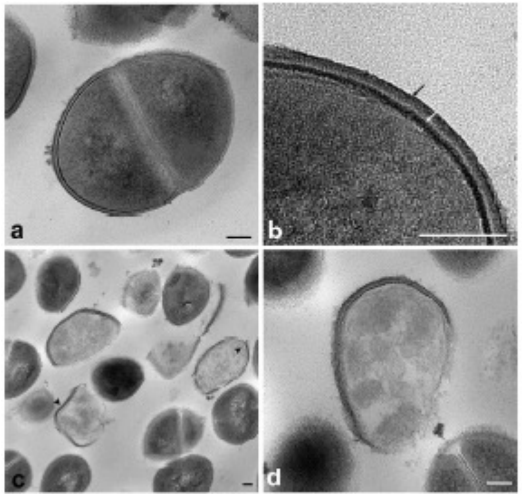
- Metallic NPs (especially, Ag and Cu) are usually reactive to phosphorus or compounds which are included in cell wall of bacteria, inducing the denaturation of wall protein.
- Attached metallic NPs destroy cell wall and change cell permeability, which alters bacterial metabolism.
- Then, cytoplasm of bacteria is leaked through destroyed cell wall.

[1] Lemire, et al. Antimicrobial activity of metals: mechanisms, molecular targets and applications, *Nature Reviews Microbiology*, 2013, 11: 371-384.

Antimicrobial mechanisms via metallic ions

❖ Interaction with cell membrane [1,2]



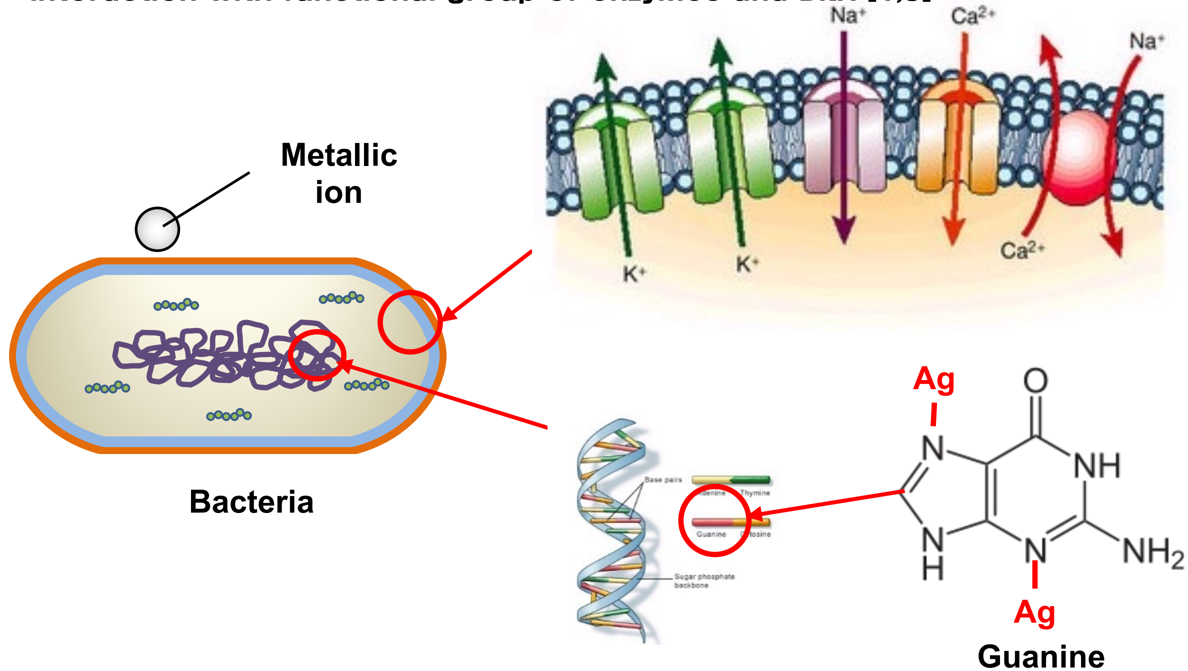


- Also, metallic ion can destroy cell wall.
- The mechanism of the antimicrobial action of metallic ions is closely related to their interaction with thiol (sulfhydryl) groups included in amino acids, such as cysteine, which composes cell wall.

$$R\text{-}SH + Ag^{+} \leftrightarrow R\text{-}S\text{-}Ag + H^{+}$$ [2]

[1] Lemire, et al. *Nature Reviews Microbiology*, 2013, 11: 371-384.
[2] Jung, et al. *Applied and Environmental Microbiology*, 2008, 74: 2171-2178.

❖ Interaction with functional group of enzymes and DNA [1,3]

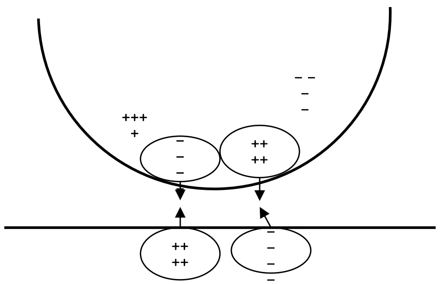


- Metallic ion이 세포의 plasma나 cytomembrane 의 효소 functional group과 결합하여, 세포 내의 K^+ 이온을 방출 시키는 역할을 하여 세포를 불활성화 시킴
- Ag ion의 경우, 세포 내 구성물 중에서 인산 그룹 보다 DNA와 더 잘 반응하는 성질이 있으므로, DNA와 반응하여 세포분열을 제지하는 역할을 함. 또한 DNA의 구아닌 성분 중 질소와 결합하여 DNA를 변형을 야기함.

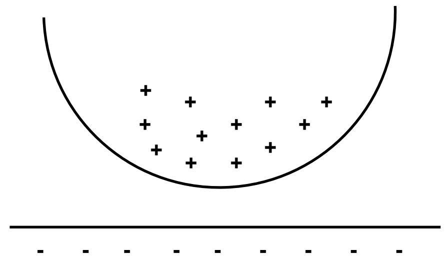
[1] Lemire, et al. *Nature Reviews Microbiology*, 2013, 11: 371-384.
[3] Benetti, et al. *Materials*, 2020, 13: 784.

Detachment of Particles

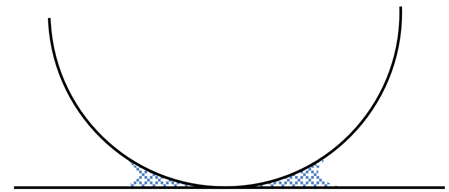
◆ Adhesive forces



< Van der Waals adhesive force >



< Adhesive force due to a electrostatic force>



< Adhesive force due to a liquid film >

$$F_{adh} = \frac{Ad}{12x^2}$$

A : hamaker constant,
d: Particle diameter
x: separation distance

$$F_{adh} = \frac{K_E q^2}{x_q^2}$$

K_E : constant of proportionality,
q : charge
x_q : separation distance of opposite charges

$$F_{adh} = 2\pi\gamma d$$

γ : surface tension of the liquid
d : particle diameter

Diameter (μm)	Force(N)		
	Adhesion	Gravity	Air current (at 10m/s)
0.1	**10^{-8}**	5×10^{-18}	**2×10^{-10}**
1.0	**10^{-7}**	5×10^{-15}	**2×10^{-9}**
10	10^{-6}	5×10^{-12}	3×10^{-8}

•Ref) "Aerosol Technology", Hinds (1990)

Theory of an electrostatic precipitator

Deutsch equation

$$\eta = 1 - e^{-wA/Q}$$

w : Migration velocity
A : Collection area
Q : Flow rate

W. Deutsch, *Ann. Phys.* (1922)

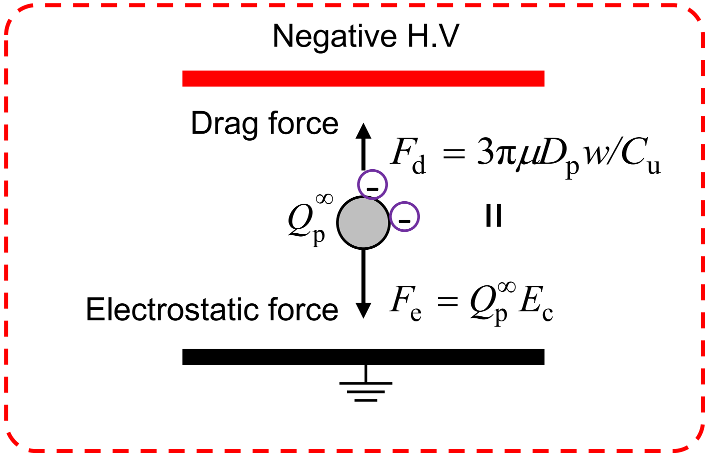
Migration velocity

$$w = \frac{C_u Q_p^{\infty} E_c}{3\pi \mu D_p}$$

μ : Dynamic viscosity of air
D_p : Particle diameter
Q_p^{∞} : Charge of a particle
C_u : Cunningham correction factor
E_c : Electric field of collection stage

$$C_u = 1 + 1.246\left(2\lambda/D_p\right) + 0.42\left(2\lambda/D_p\right)e^{-0.87/\left(2\lambda/D_p\right)}$$

K. R. Parker., *"Applied electrostatic precipitator"* (1922)



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Q_p^{∞} : Charge of a particle
μ : Dynamic viscosity of air
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E_c : Electric field of collection stage

Cochet's charging theory

$$Q_p^{\infty} = \left\{\left(1 + 2\lambda/D_p\right)^2 + \left(\frac{2}{1 + 2\lambda/D_p}\right) \cdot \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)\right\} \cdot \pi \varepsilon_0 D_p^2 E_p$$

λ : Mean free path
ε_0 : Vacuum permittivity
ε_r : Relative permittivity of a particle
E_p : Electric field of pre-charging stage

R. Cochet, *Colloque International La Physique Des Forces Electrostatiques Et Leurs Application* (1961)

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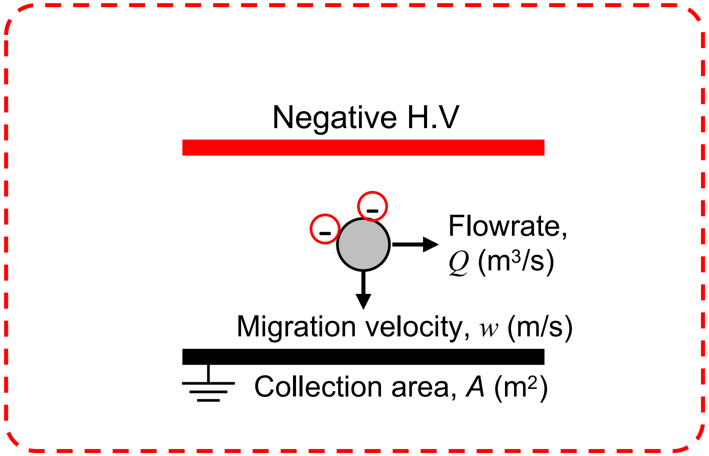

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