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LETTER

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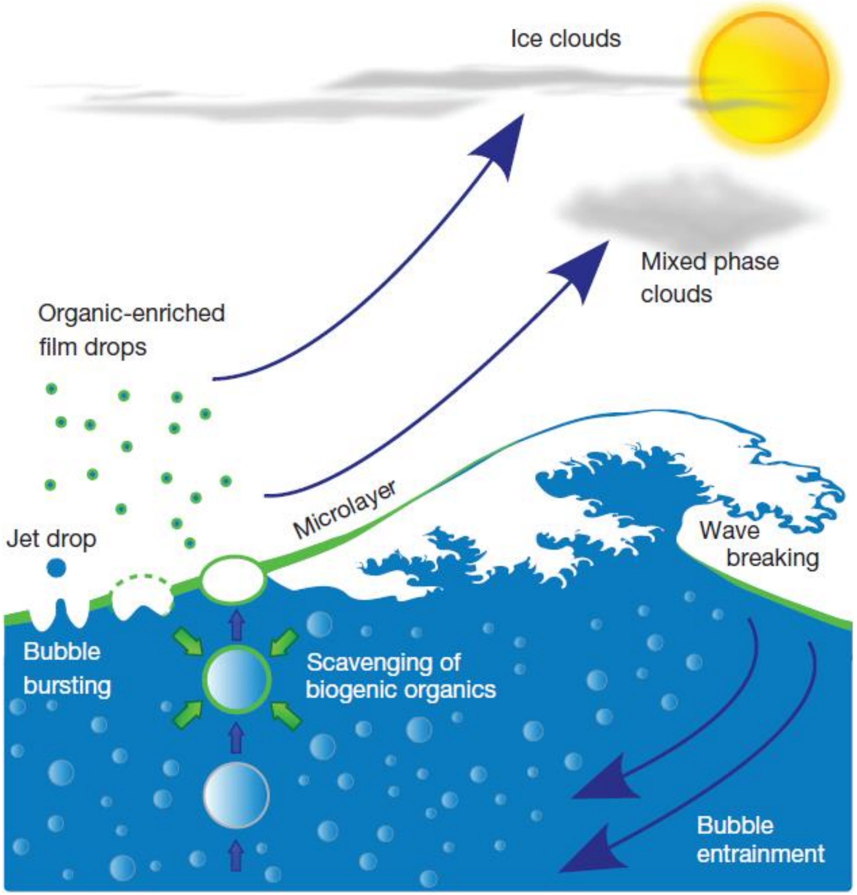
A marine biogenic source of atmospheric ice-nucleating particles



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Aerosol generation by raindrop impact on soil

Young Soo Joung[1] & Cullen R. Buie[1]

COLLOQUIUM INTRODUCTION

Improving our fundamental understanding of the role of aerosol—cloud interactions in the climate system

Clouds play a key role in Earth's radiation budget, and aerosols serve as the seeds upon which cloud droplets form. Anthropogenic activity has led to an increase in aerosol particle concentrations globally and an increase in those particles that act as cloud condensation nuclei (CCN) and ice nucleating particles (INP).

Materials and method

3 bacterial species were taken that abundant in soil:

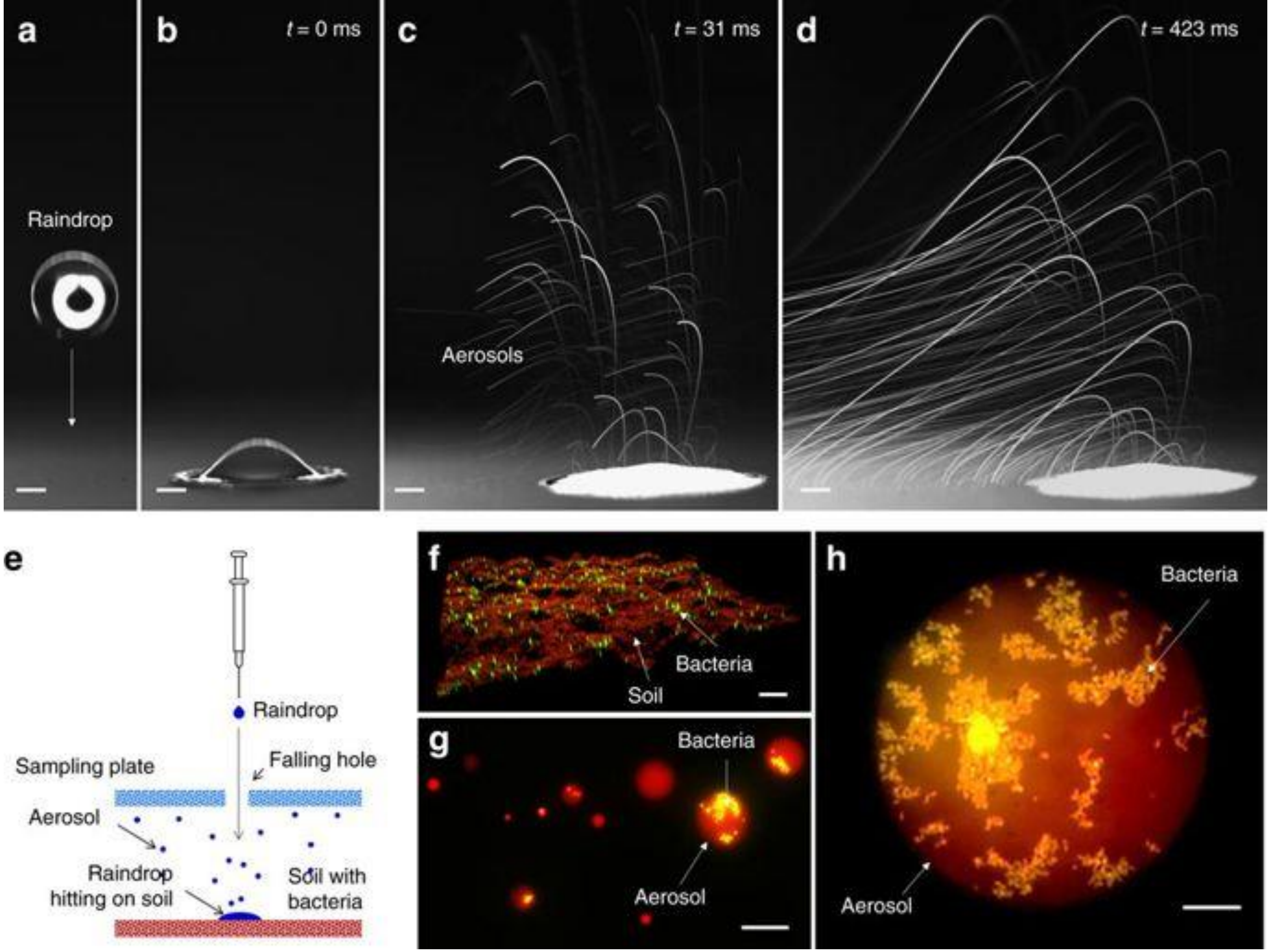
1. *Corynebacterium glutamicum*
2. *Bacillus subtilis*
3. *Pseudomonas syringae*

TLC plates, clay, sand clay and sand were used as representative soil

PS microsphere were used to determine aerosol efficiency.

Factors taken into consideration:

1. Velocity of droplet (impact velocity)
2. Surface temperature
3. Wettability of surface
4. No. of bubbles

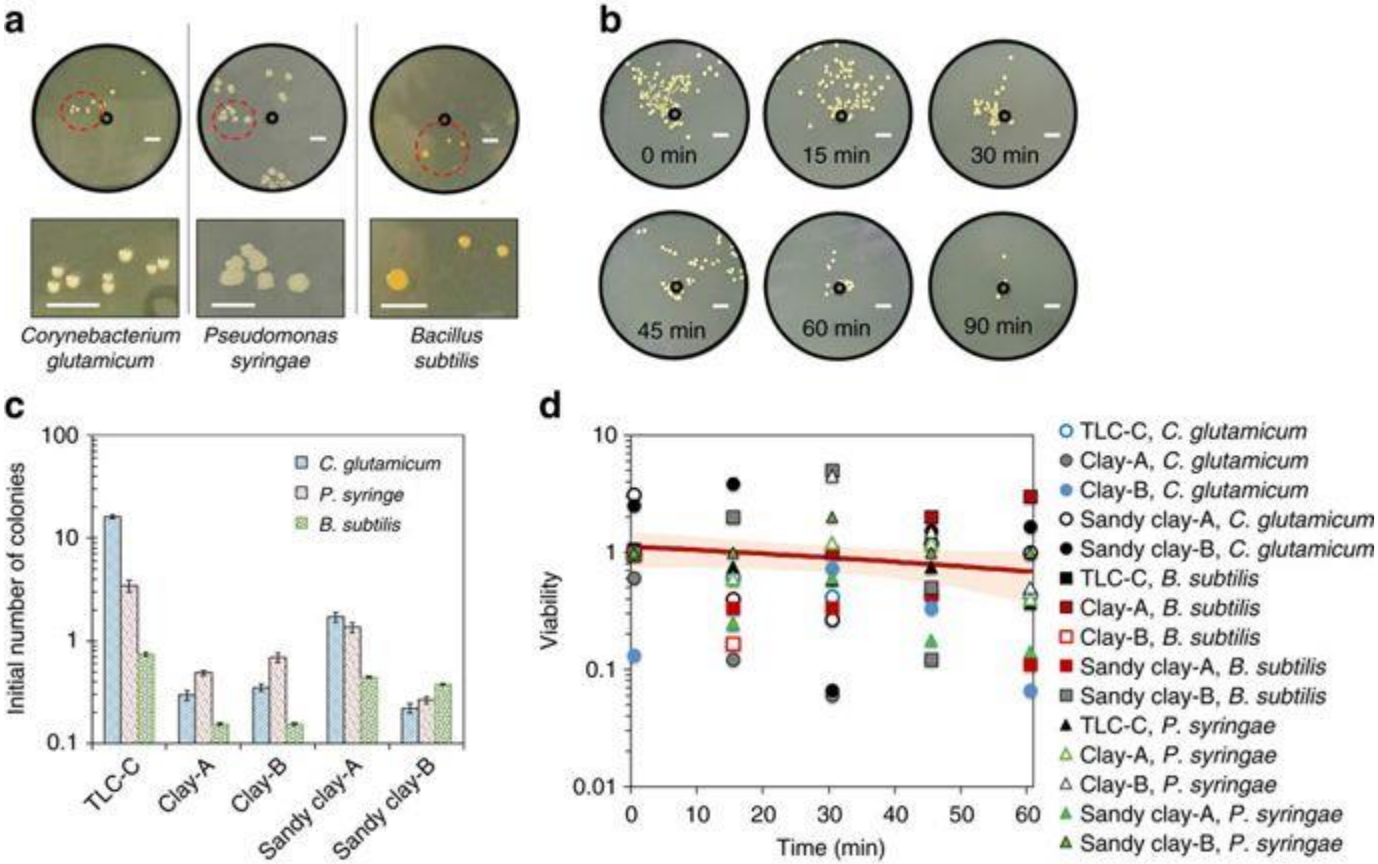


(**a**–**d**) Aerosols generated by drop impingement on a reference surface, which maximized the aerosol generation (a TLC plate (TLC-C) in Table 1). The TLC plates served as an ideal soil-like surface. The white lines are the trajectories of aerosols ejected from the initial droplet after impact over a period of 400 ms. Due to air flow above the droplet, the trajectories of the ejected aerosols are curved. The scale bars indicate 1 mm. (**e**) Schematic illustration of the experimental procedure for drop impingement on soil and aerosol collection. (**f**) Confocal microscopy images of *C. glutamicum* on the surface of clay soil with the cell density of 250 cells mm^{-2}. (**g**,**h**) Fluorescent microscopy images of aerosols generated by drop impingement on clay soil pre-permeated with *C. glutamicum*. The red circles and the yellow dots indicate aerosols and *C. glutamicum*, respectively. The scale bars indicate 200, 50 and 25 μm in **f**–**h**, respectively.

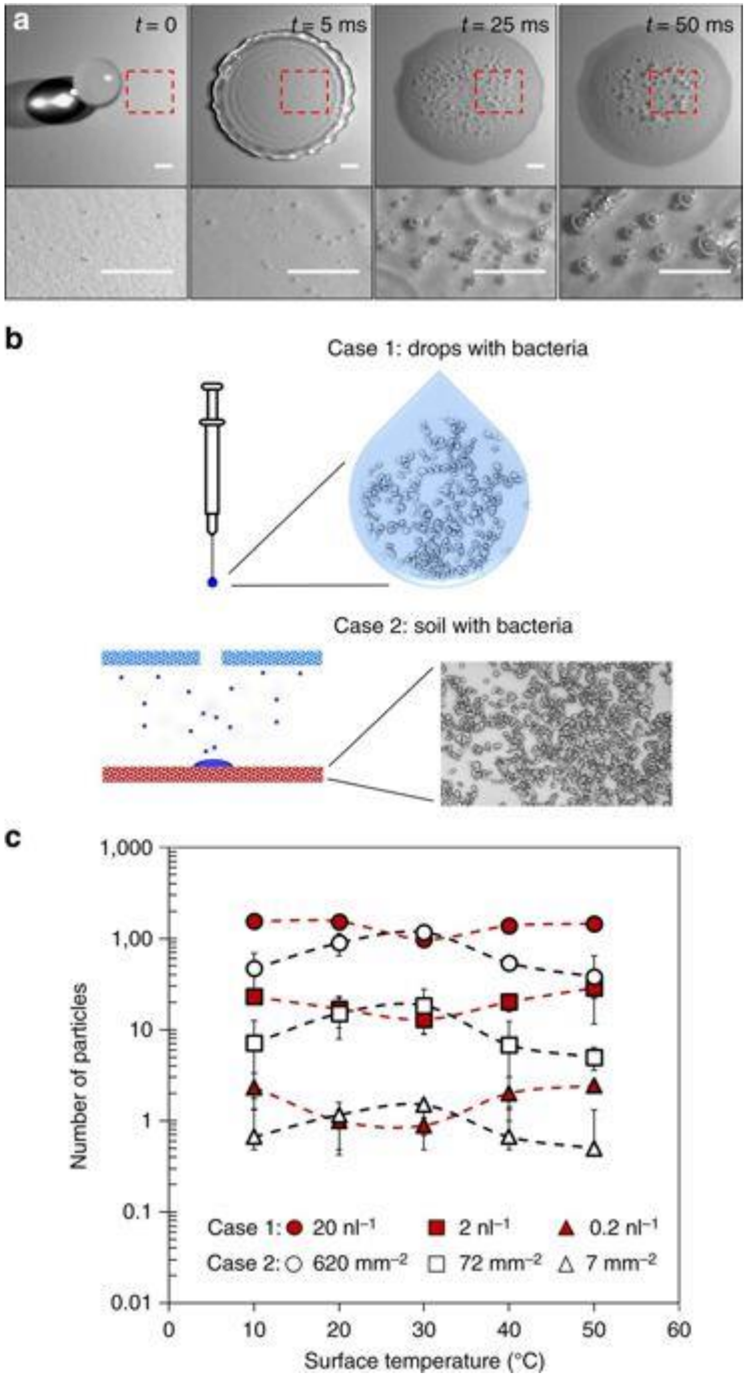
Table 1 | Surface properties related to bioaerosol generation by raindrops impinging on soils and TLC plates.

Media	Media hydraulic diffusivity	Critical surface temp.	Critical impact speed	Aerosolization efficiency: ε (%)				
Name	D_{cap} ($mm^2 s^{-1}$)	T_c (°C)	V_c ($m s^{-1}$)	1 μm latex bead	10 μm latex bead	*C. glutamicum*	*P. syringae*	*B. subtilis*
TLC_A	9.5	30	1.4	0.16	2.34	0.093	NA	NA
TLC_C	22.4	30	1.33	2.24	2.68	0.16	0.034	0.0074
$Clay_A$	2.6	30	1.53	0.15	0.87	0.004	0.0066	0.0021
$Clay_B$	1.4	40	1.33	0.15	3.56	0.02	0.0392	0.0088
Sandy $clay_A$	12	20	1.47	0.83	NA	0.013	0.0103	0.0034
Sandy $clay_B$	4.8	50	1.33	1.24	NA	0.0060	0.0072	0.0102
$Sand_A$	127.6	30	1.53	0.01	0.05	NA	NA	NA
$Sand_B$	252.8	NA	NA	NA	NA	NA	NA	NA

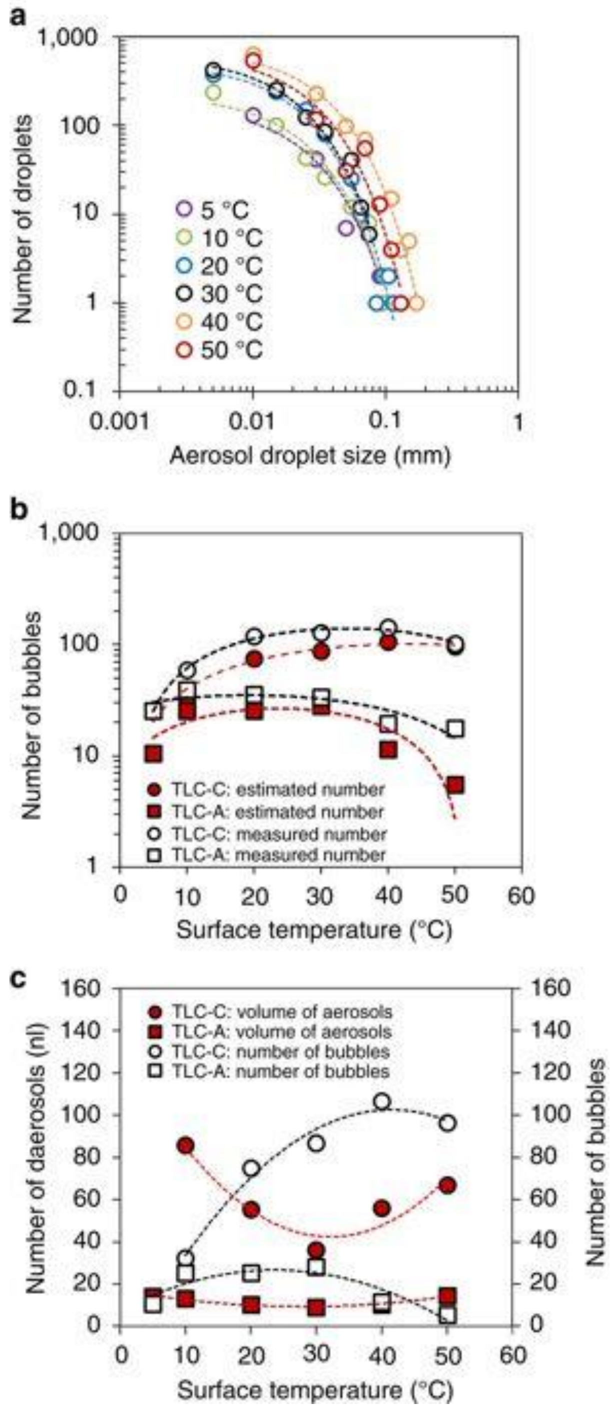
D_{cap}, T_c and V_c are hydraulic diffusivity[54], critical temperature and critical impact velocity of the surfaces, respectively. In the case of $Sand_A$ and $Sand_B$, the dispersion of bacteria was not observed due to the low aerosolization efficiency; especially any particles and bacteria were not transferred by raindrops on $Sand_B$.



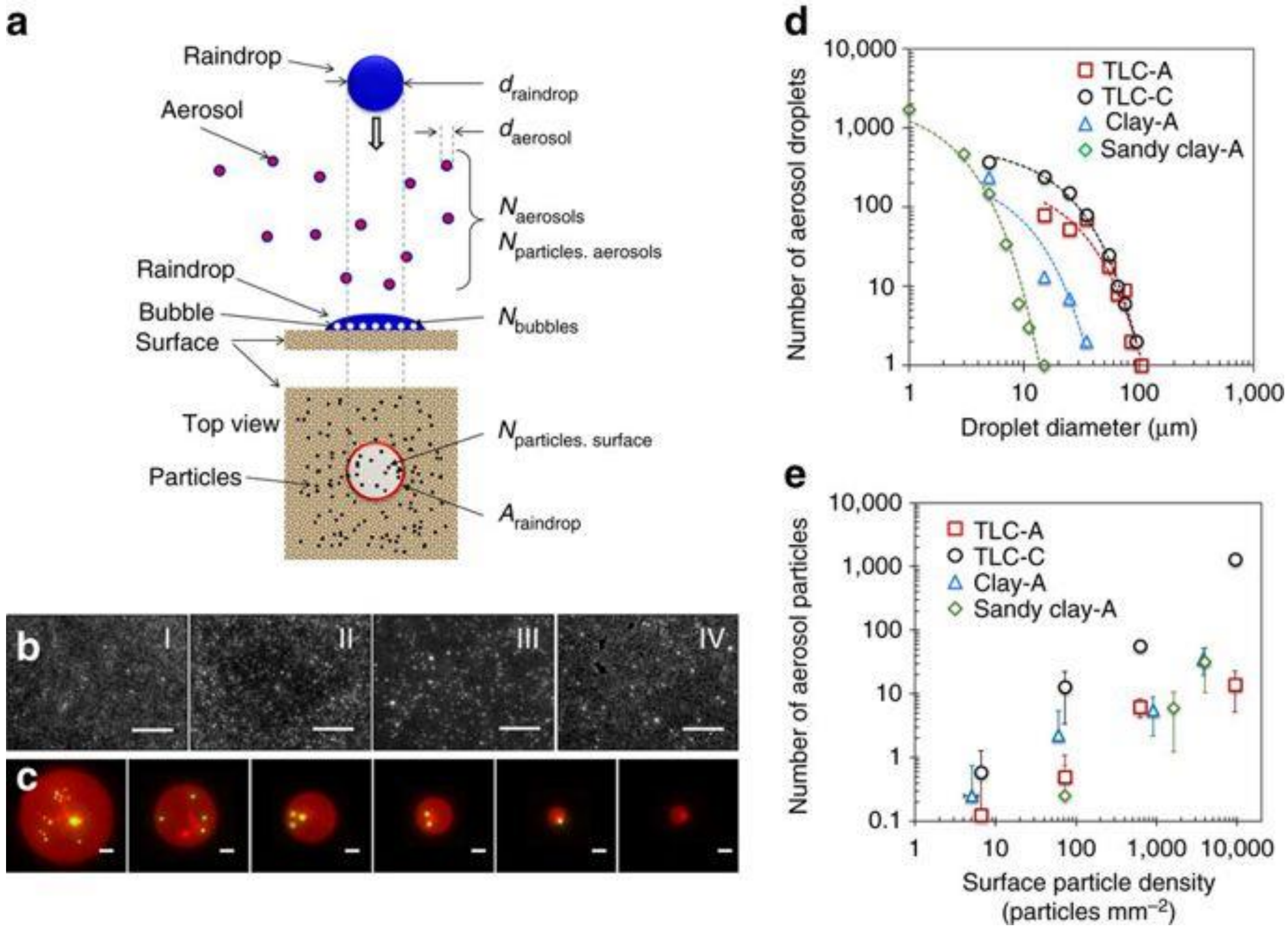
(**a**) Colonies of three kinds of soil bacteria, *C. glutamicum*, *P. syringae* and *B. subtilis*, cultured on agar plates for 2 days after they were aerosolized by raindrops on sandy-clay soil (Sandy clay-A in Table 1). The inner black circles indicate the location where raindrops hit on the soil. The yellow dots indicate the colonies where bacteria grew. The scale bars represent 10 mm. (**b**) Viability test with respect to the duration of drying the aerosols collected on the sampling plates. The time, displayed in the images, indicate the drying duration. Aerosols were generated from TLC plates (TLC-C in Table 1) pre-permeated with *C. glutamicum*. The colonies were cultured on agar plates for 2 days after the aerosolization. The scale bars indicate 10 mm. (**c**) Average number of colony-forming units from a single raindrop when the aerosols, collected on the sampling plates, were transferred to the agar plates immediately after aerosolization. The error bars represent±1 s.d. resulting from nine drop impingements. The impact velocity was 1.4 m s^{-1}, the drop diameter of 2.8 mm, and the surface temperature 20 °C for all cases. (**d**) Viability of bacteria with respect to time after aerosolization. The viability is the ratio of the number of colonies on the agar plate to the number of aerosols containing bacteria collected on the sampling plate.



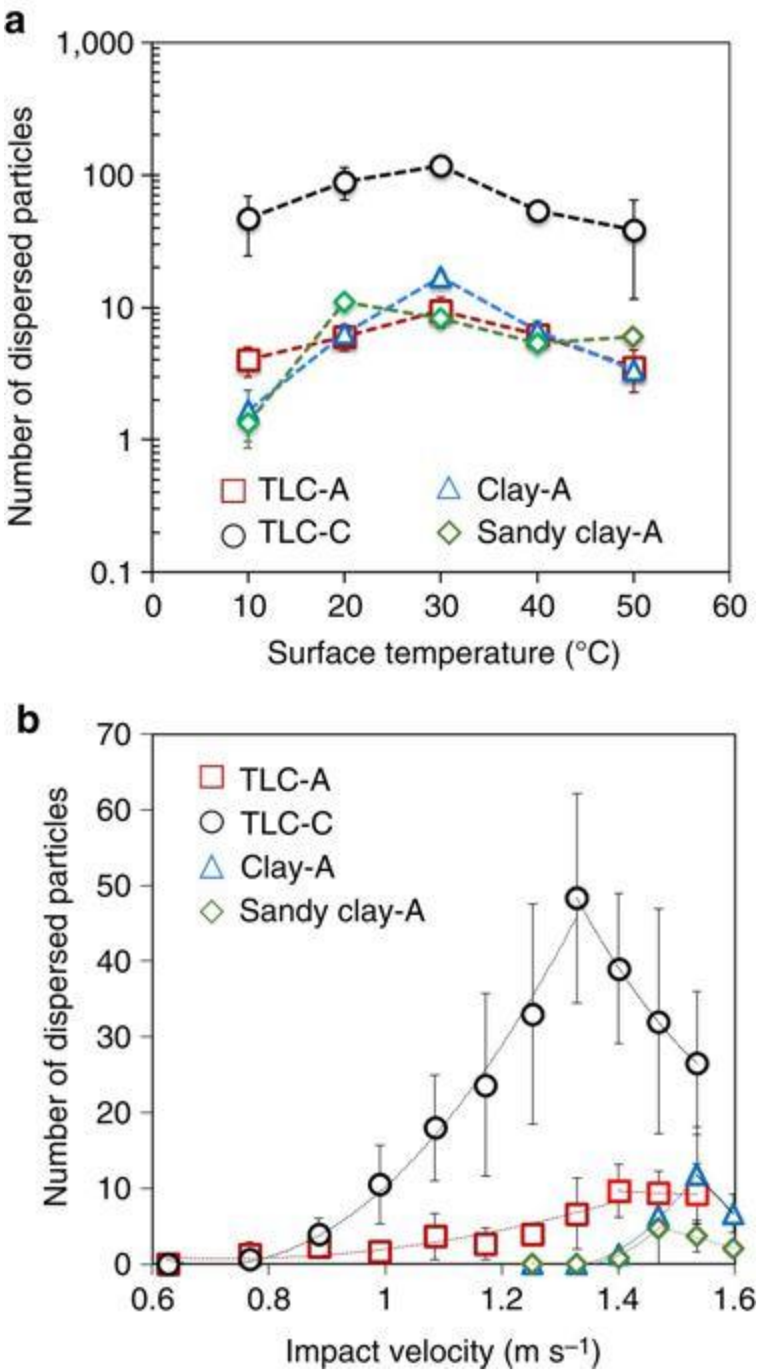
(**a**) Bubble formation at the interface of surface and raindrop. The red boxes indicate the regions magnified in the images below. The scale bars represent 1 mm. (**b**) Schematic illustrations of the two cases of bacteria existence. Bacteria can exist inside the raindrop (Case 1) or on the surface (Case 2). (**c**) The number of particles dispersed by aerosols generated on a TLC (TLC-C) plate with respect to surface temperature. Drop impingements were conducted with two different initial conditions: first, particles are in the raindrops (Case 1) and second, particles are on the surfaces (Case 2). In Case 1 and Case 2, different particle concentrations and densities were used; Case 1: 20 particles per nl, 2 particles per nl, and 0.2 particles per nl; Case 2: 620 particles per mm^2, 72 particles per mm^2, and 7 particles per mm^2. For both cases, 1 μm diameter yellow-green fluorescent microspheres were used. The red symbols and the white symbols indicate the drop impingements of Case 1 and Case 2, respectively. The error bars represent±1 s.d. resulting from nine drop impingements.



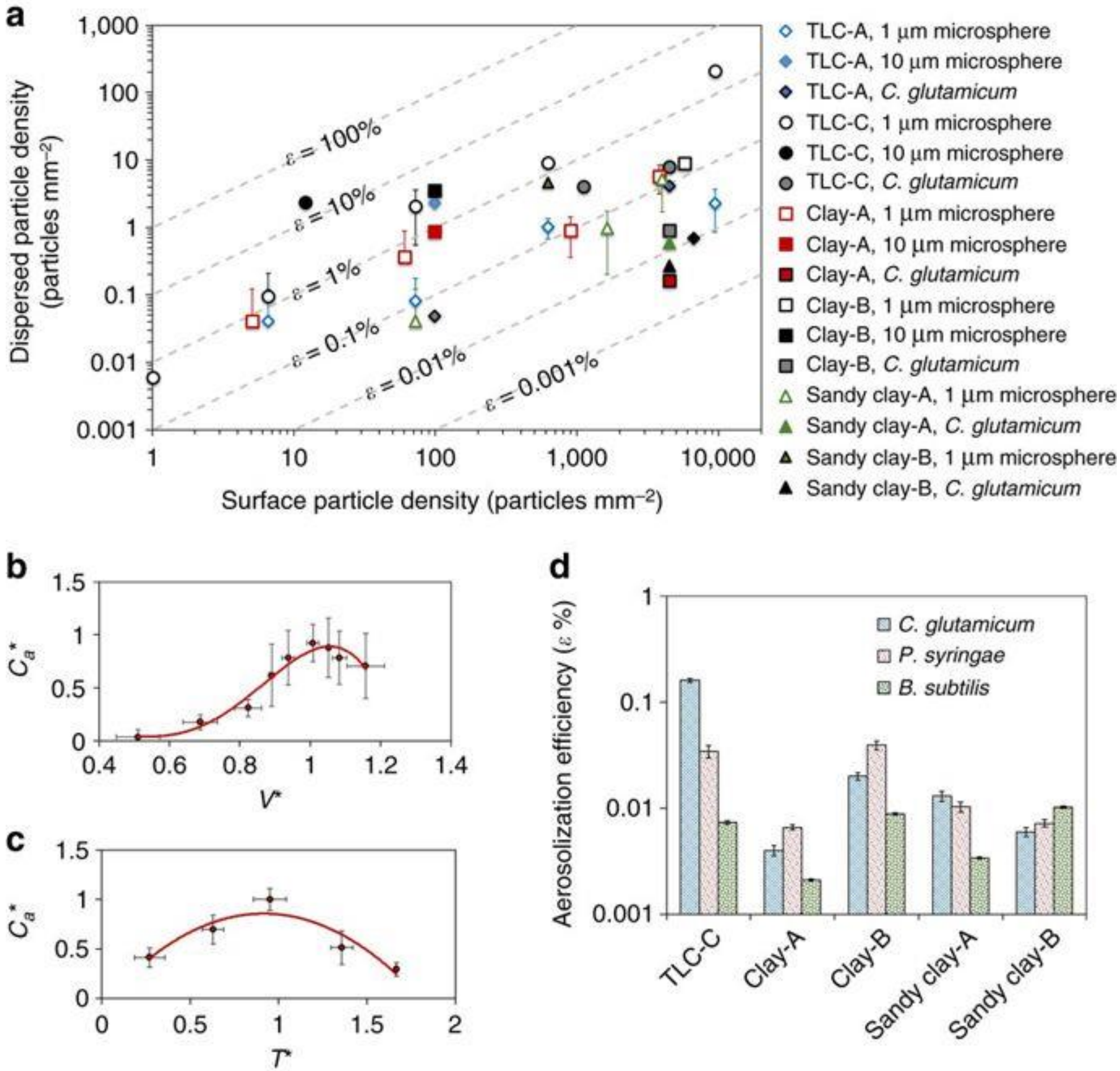
(**a**) The number of aerosols as a function of aerosol diameter. From the curves, we can estimate the number of bubbles formed inside the raindrop as a function of surface temperature. The impact velocity was 1.4 m s^{-1} with the raindrop diameter of 2.8 mm for all the surface temperatures. (**b**) The number of bubbles estimated by the theory (the red symbols) and counted using high-speed images (the white symbols). The theoretical data were estimated by curve fittings and an empirical equation. (**c**) The number of bubbles created inside a droplet (the white symbols) and the total volume of aerosols (the red symbols) with respect to surface temperature.



(**a**) Schematic illustration of the key parameters related to particle dispersion by raindrop impact. (**b**) Fluorescence microscopy images of surfaces with different particle densities. The bright dots are 1 µm diameter yellow-green fluorescent microspheres. The approximate surface particle density of images I, II, III and IV are 10, 10^2, 10^3 and 10^4 particles per mm^2, respectively. The scale bars represent 500 µm. (**c**) Aerosols containing 1 µm microspheres and collected on a sampling plate. The scale bars represent 25 µm. (**d**) The number of aerosols decreases exponentially with respect to aerosol diameter. (**e**) The total number of microspheres dispersed by a single raindrop is linearly proportional to the surface density of the microspheres. The surface temperature is 25 °C and the raindrop velocity at impact is 1.4 m s^{-1} for **d** and **e**. The error bars indicate±1 s.d. resulting from nine drop impingements. The dotted lines in **d** indicate exponential fitting lines.



(**a**) The number of particles dispersed by a single drop impingement with respect to surface temperature. The surface temperature was varied from 10 to 50 °C. (**b**) The number of microspheres dispersed by aerosols at different impact velocities. Surface particle densities of TLC-A, TLC-C, and Clay-A, and Sandy clay-A are 623, 627, 1,308 and 1,725 particles per mm^2, respectively, in **a**,**b**. The raindrop velocity at impact is 1.4 m s^{-1} for **a** and the surface temperature is 25 °C for **b**. The error bars indicate±1 s.d. resulting from nine drop impingements. The dotted lines in **b** indicate the second order polynomial fitting lines.


a
Dispersed particle density (particles mm⁻²)
Surface particle density (particles mm⁻²)
ε = 100%
ε = 10%
ε = 1%
ε = 0.1%
ε = 0.01%
ε = 0.001%
TLC-A, 1 µm microsphere
TLC-A, 10 µm microsphere
TLC-A, C. glutamicum
TLC-C, 1 µm microsphere
TLC-C, 10 µm microsphere
TLC-C, C. glutamicum
Clay-A, 1 µm microsphere
Clay-A, 10 µm microsphere
Clay-A, C. glutamicum
Clay-B, 1 µm microsphere
Clay-B, 10 µm microsphere
Clay-B, C. glutamicum
Sandy clay-A, 1 µm microsphere
Sandy clay-A, C. glutamicum
Sandy clay-B, 1 µm microsphere
Sandy clay-B, C. glutamicum
b
C*a
V*
c
C*a
T*
d
Aerosolization efficiency (ε %)
C. glutamicum
P. syringae
B. subtilis
TLC-C
Clay-A
Clay-B
Sandy clay-A
Sandy clay-B

Conclusion

1. New mechanism of bioaerosol generation through impact of rain
2. These aerosols can transport the bacteria by wind, fast mode of transport
3. Surface properties pay an important role in determining the aerosolization efficiency.
4. Surface temperature and impact velocity also effect the efficiency.