Bacterial Interactions and Transport in Unsaturated Porous Media

Gang Chen, Pawan Kumar Subramaniam
and Amy Chan Hilton

Department of Civil & Environmental Engineering

FAMU-FSU College of Engineering

Potential groundwater contamination with pathogens

Wastewater reclamation for irrigation

- In California, 60% of recycled wastewater used for irrigation

Animal waste applications

- In US, approximately 1.3 billion tons of animal manure generated annually
- Land applications

St Mark River

Fecal Coliform
16 ~ 100/100 ml

Vision of Animal Waste Management

- **Challenged with finding a balance between land applications and environmental protection**

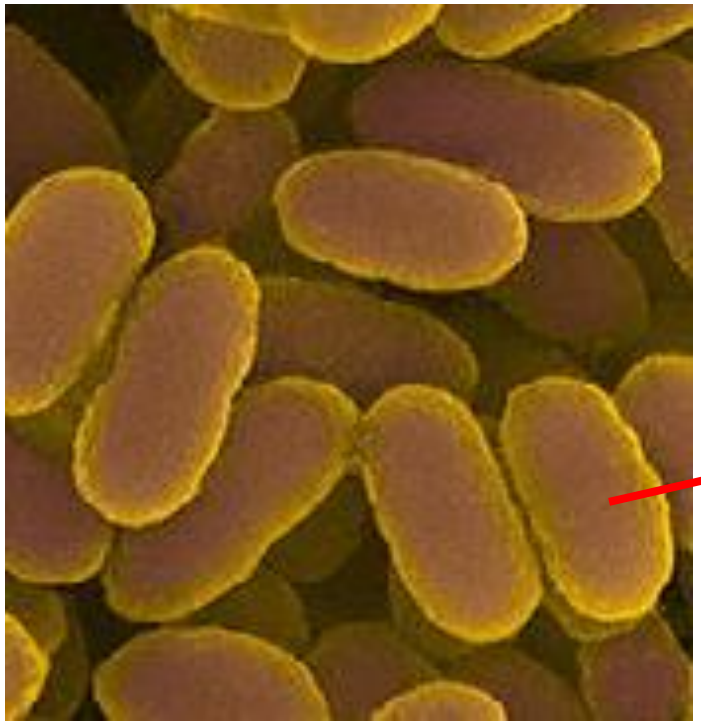
- **Provide education and training in growth biology, efficient nutrient management and environmental protection**

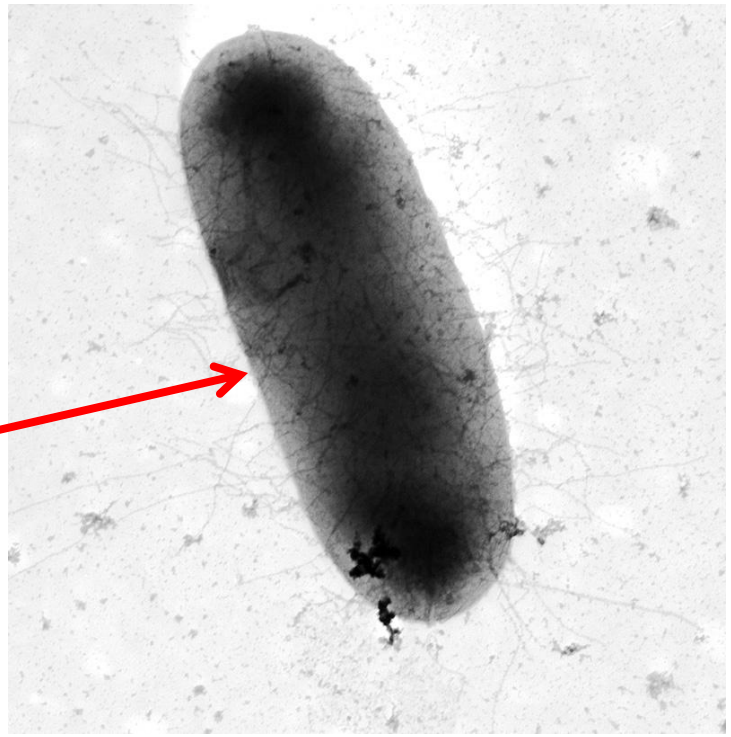
- **Solid theoretical background in Agricultural Engineering, Biological System Engineering and Environmental Science & Engineering, etc., focusing on applications**

Objectives

- Bacterial interaction quantification
- Bacterial transport model structures and formulations
- Surface thermodynamic characterization applications

Bacterial Strain





***E. Coli* HB101**

A plasmidless non-fimbriated bacterium, obtained from ATCC (33694)

Bacterial Strain

P. fluorescens ***B. subtilis***

Obtained from ATCC (17559 and 6051a)

Bacterial Surface Property Quantification

γ^{LW} γ^{+} γ^{-} ζ

γ^{LW}– Liftshitz-van der Waals component surface tension (mJ/m^2)

γ^{+} – Electron-acceptor parameter of Lewis acid/base component surface tension (mJ/m^2)

γ^{-} – Electron-donor parameter of Lewis acid/base component surface tension (mJ/m^2)

ζ – Zeta potential (mV)

van Oss-Chaudhury-Good Equation

Solve for γ_S^{LW}, γ_S^{+} and γ_S^{-}

$$(1+\cos\theta)\gamma_L = 2\left(\sqrt{\gamma_S^{LW}\gamma_L^{LW}} + \sqrt{\gamma_S^{+}\gamma_L^{-}} + \sqrt{\gamma_S^{-}\gamma_L^{+}}\right)$$

$$\begin{cases} (1+\cos\theta_1)\gamma_1 = 2\left(\sqrt{\gamma_S^{LW}\gamma_1^{LW}} + \sqrt{\gamma_S^{+}\gamma_1^{-}} + \sqrt{\gamma_S^{-}\gamma_1^{+}}\right) \\ (1+\cos\theta_2)\gamma_2 = 2\left(\sqrt{\gamma_S^{LW}\gamma_2^{LW}} + \sqrt{\gamma_S^{+}\gamma_2^{-}} + \sqrt{\gamma_S^{-}\gamma_2^{+}}\right) \\ (1+\cos\theta_3)\gamma_3 = 2\left(\sqrt{\gamma_S^{LW}\gamma_3^{LW}} + \sqrt{\gamma_S^{+}\gamma_3^{-}} + \sqrt{\gamma_S^{-}\gamma_3^{+}}\right) \end{cases}$$

Interaction Free Energy Calculation

$$\Delta G_{132}^{TOT} = \Delta G_{132}^{LW} + \Delta G_{132}^{AB} + \Delta G_{132}^{EL}$$

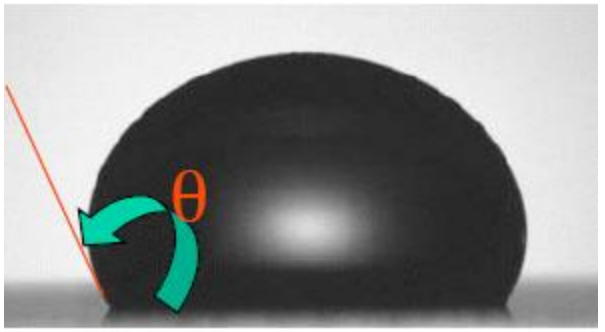
$$\Delta G(y)_{132}^{LW} = -4\pi \frac{y_0^2}{y} R[(\sqrt{\gamma_3^{LW}} - \sqrt{\gamma_2^{LW}})(\sqrt{\gamma_3^{LW}} - \sqrt{\gamma_1^{LW}})]$$

$$\Delta G(y)_{132}^{AB} = 4\pi R y_0 e^{(y-y_0)/\lambda} [(\sqrt{\gamma_1^+} - \sqrt{\gamma_2^+})(\sqrt{\gamma_1^-} - \sqrt{\gamma_2^-}) - (\sqrt{\gamma_1^+} - \sqrt{\gamma_3^+})(\sqrt{\gamma_1^-} - \sqrt{\gamma_3^-}) - (\sqrt{\gamma_2^+} - \sqrt{\gamma_3^+})(\sqrt{\gamma_2^-} - \sqrt{\gamma_3^-})]$$

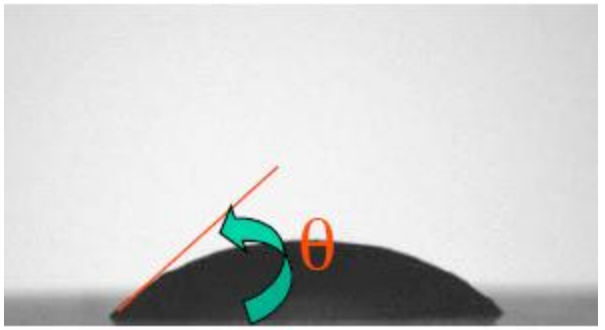
$$\Delta G(y)_{132}^{EL} = \pi \varepsilon \varepsilon_0 R[2\psi_1\psi_2 Ln(\frac{1+e^{-\kappa y}}{1-e^{-\kappa y}}) + (\psi_1^2 + \psi_2^2) Ln(1-e^{-2\kappa y})]$$

Contact Angle Measurement

A : Moisture-controlled Chamber
B : Sample platform
C : Syringe holder
D : Camera with imaging lens
E : Light source



Contact Angle > 90°



Contact Angle < 90°

Wicking Method

Kruss K100 Tensiometer

Washburn Equation

$$h^2 = (R_e \cdot t \cdot \gamma_L \cdot \cos\theta) \cdot (2 \cdot \mu)^{-1}$$

h : height of capillary rise (m)

R_e : average interstitial pore size (m)

t : measuring time (sec)

γ_L : Measuring liquid surface tension (mJ/m^2)

μ : measuring liquid viscosity ($N \cdot s/m^2$)

Column Experiment

Bacterial Suspension

Column

Luminometer

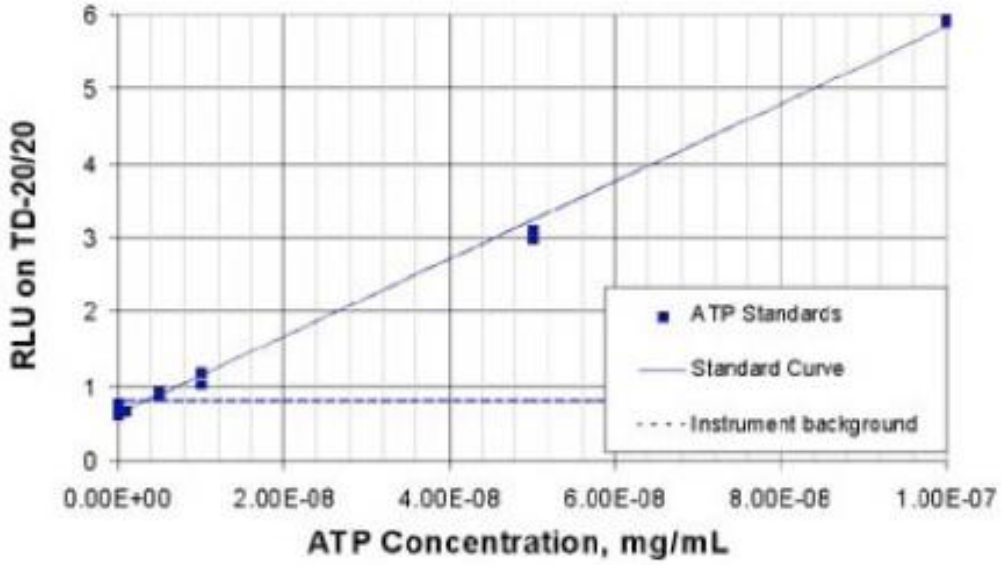
Luciferin & Luciferase

Syringe Pump

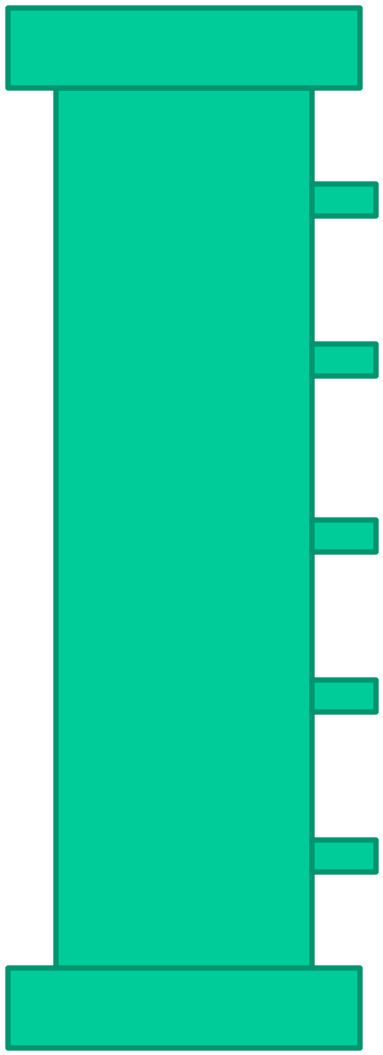
ATP Measurement

$$\text{Luciferin} + \text{ATP} + \text{O}_2 \xrightarrow{\text{Luciferase},\ \text{Mg}^{2+}}$$

$$\text{Oxyluciferin} + \text{AMP} + \text{CO}_2 + \text{PP}_i + \text{Light (560 nm)}$$



Water Content and Matric Potential



$$S_e = [1 + (\alpha h)^n]^{(1/n-1)}$$

α: inverse of the air-entry potential (m^{-1})
h: water potential (m-H_2O)
n: parameter related to pore size distribution (-)

α = 0.136 cm^{-1}
n = 4.776

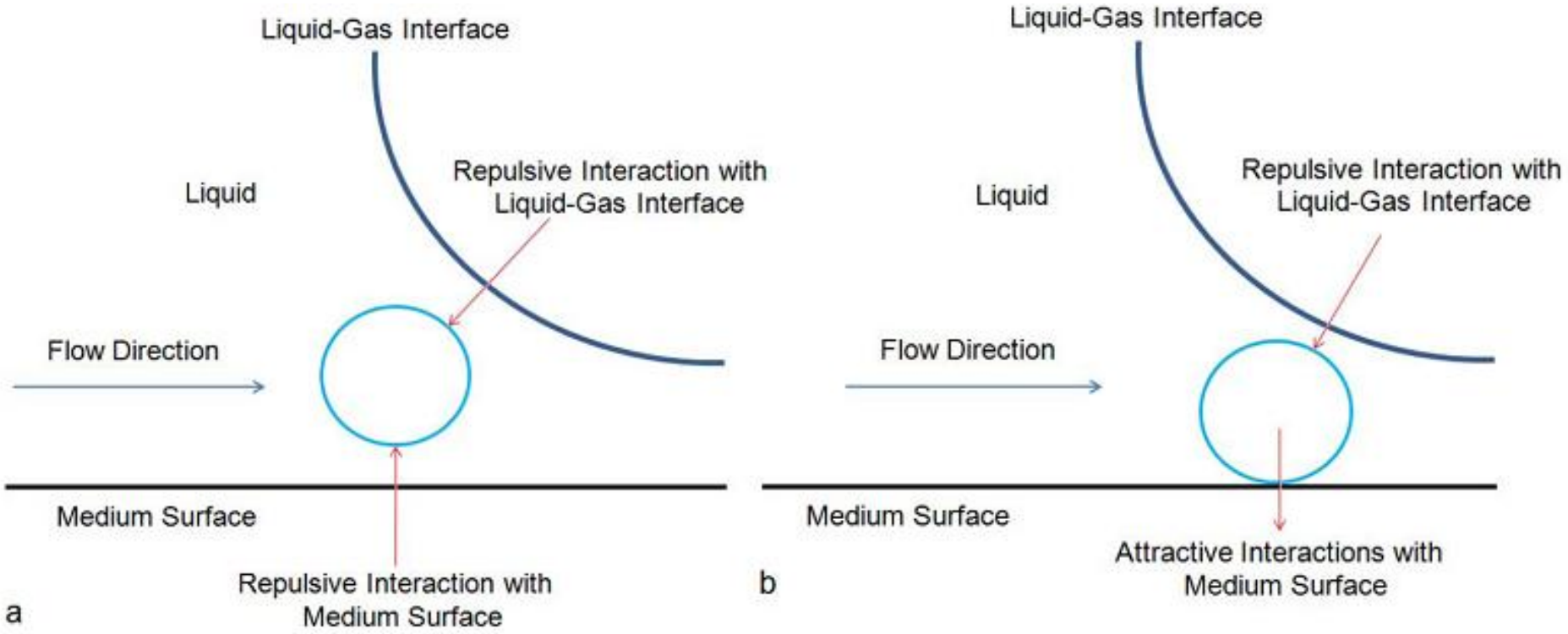
Bacterial Transport Modeling

$$\frac{\partial}{\partial t}[\theta_m C] = \frac{\partial}{\partial z}[D_z \theta_m \frac{\partial C}{\partial z}] - \frac{\partial}{\partial z}[qC] - k_1 \theta_m C + k_{des} \frac{\rho_b S}{S_e} C_r$$

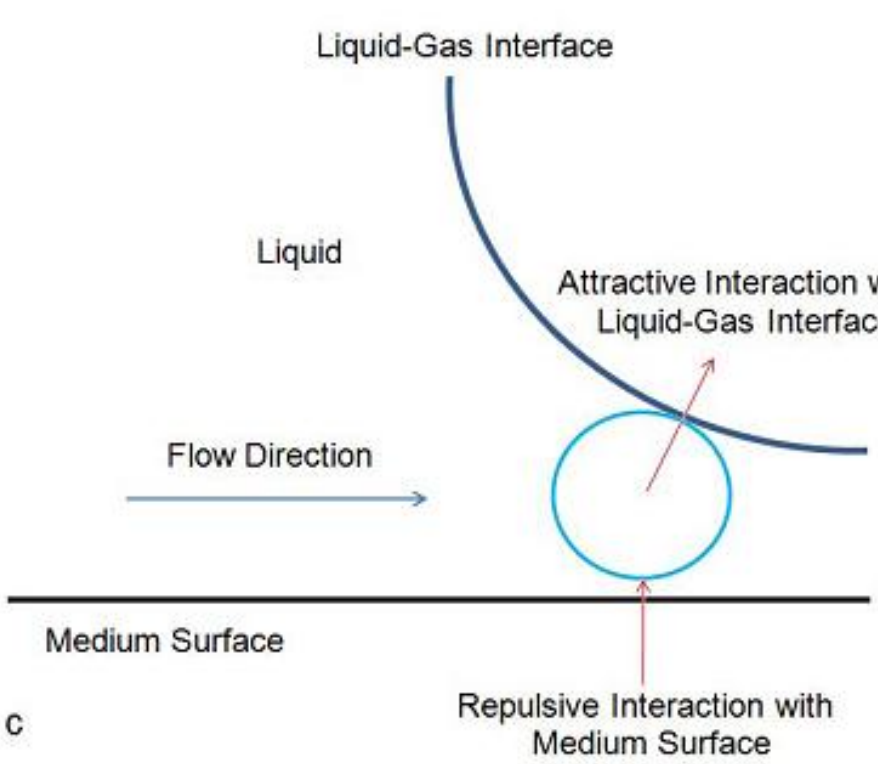
$$\frac{\partial C_r}{\partial t} = k_1 \frac{\theta_m S_e}{\rho_b S} C - k_{des} C_r$$

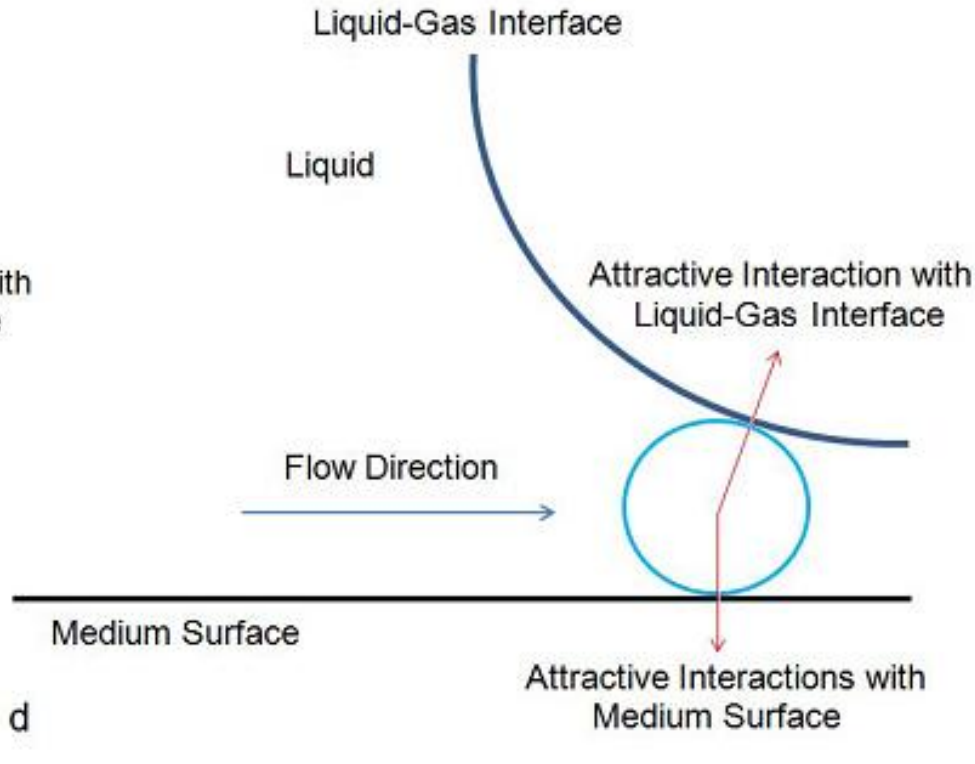
C — bacterial concentration in the solution (cells/m^3)
C_r — retained bacterial concentration [cells/(g)(m^2/m^3)]
D_z — apparent dispersion coefficient (m^2/sec)
θ_m — moisture content (m^3/m^3)
q — specific discharge (Darcian fluid flux) (m/sec)
k_1 — deposition coefficient (sec^{-1})
k_{des} — desorption coefficient (sec^{-1})
ρ_b — bulk density (g/m^3)
S — air-water interfacial area (m^2/m^3)

Bacterial Retention Mechanism



Bacterial Retention Mechanism





Bacterial Interactions with Porous Media

	ΔG_{132}^{LW} (kT)	ΔG_{132}^{AB} (kT)	ΔG_{132}^{EL} (kT)	$\Delta G_{132}^{LW+AB+EL}$ (kT)
E. coli	-36.3	1234.8	17.8	1216.3
P. fluorescens	-17.6	649.6	0.48	632.5
B. subtilis	-119.6	3023.4	467.0	3370.8

k is the Boltzmann constant (1.38×10^{-23} J/K) and T is absolute temperature (K). At 25°C, 1 kT = 4.11×10^{-21} J.

ΔG_{132}^{LW}, ΔG_{132}^{AB} and ΔG_{132}^{EL} evaluated at the equilibrium distance where physical contact between bacteria and media surface and between bacteria and air-water interface occurred.

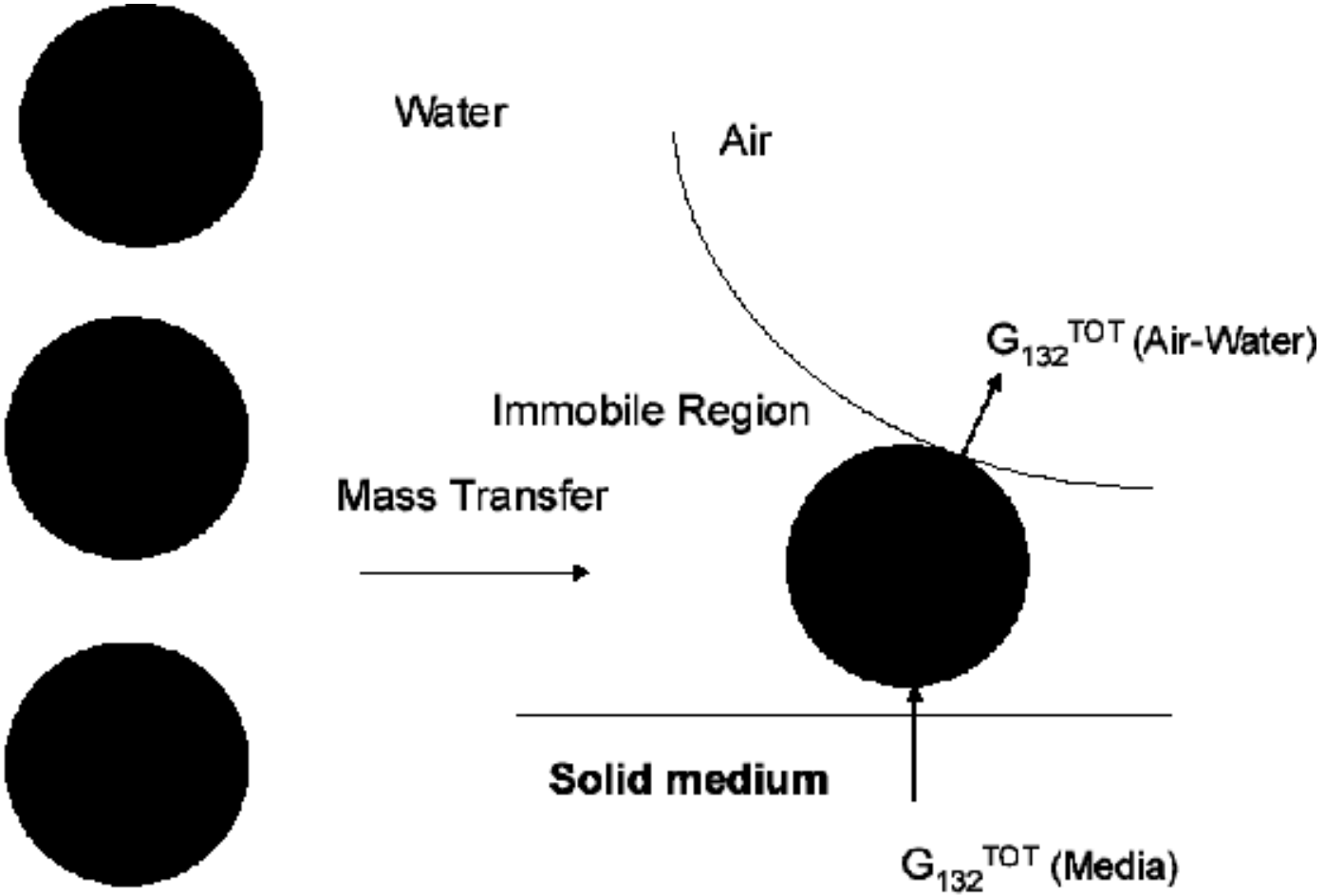
Bacterial Interactions with Air-Water Interface

	ΔG_{132}^{LW} (kT)	ΔG_{132}^{AB} (kT)	ΔG_{132}^{EL} (kT)	$\Delta G_{132}^{LW+AB+EL}$ (kT)
E. coli	-7146.9	-3030.0	1481.1	-8695.8
P. fluorescens	-4080.2	-1726.5	917.3	-4889.4
B. subtilis	-19845.9	-6740.9	2611.6	-23975.2

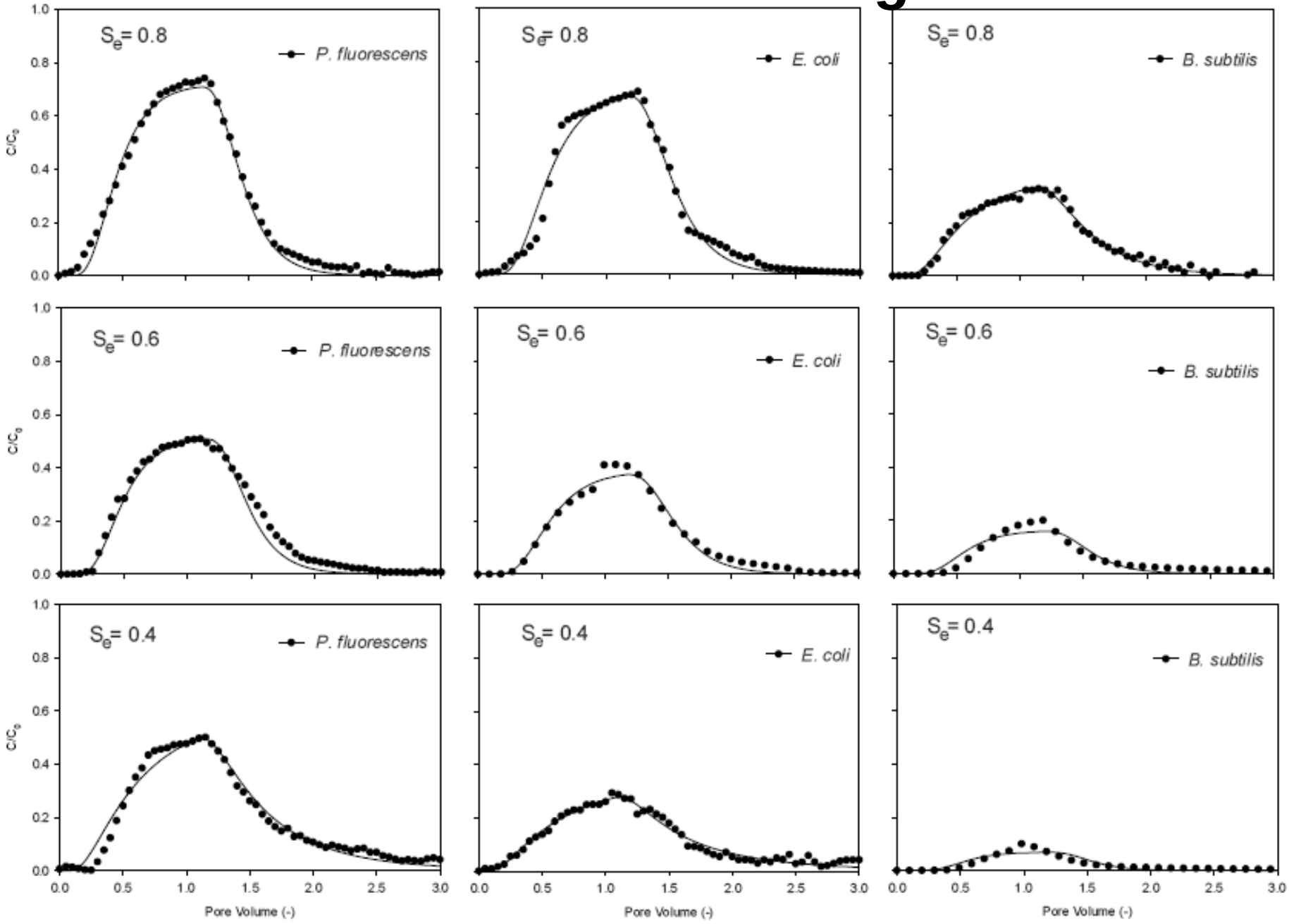
k is the Boltzmann constant (1.38×10^{-23} J/K) and T is absolute temperature (K). At 25°C, 1 kT = 4.11×10^{-21} J.

ΔG_{132}^{LW}, ΔG_{132}^{AB} and ΔG_{132}^{EL} evaluated at the equilibrium distance where physical contact between bacteria and media surface and between bacteria and air-water interface occurred.

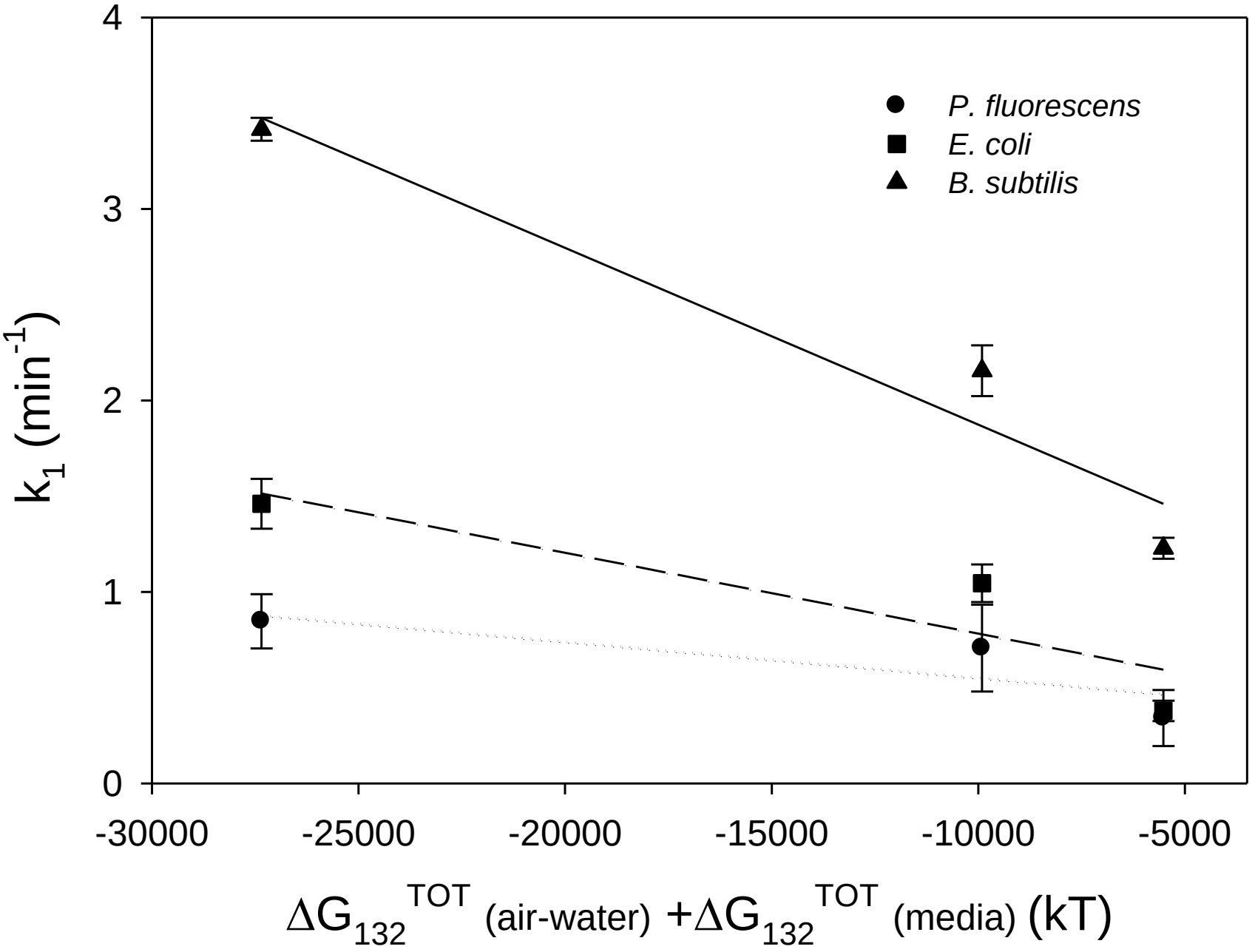
Bacterial Retention Mechanism



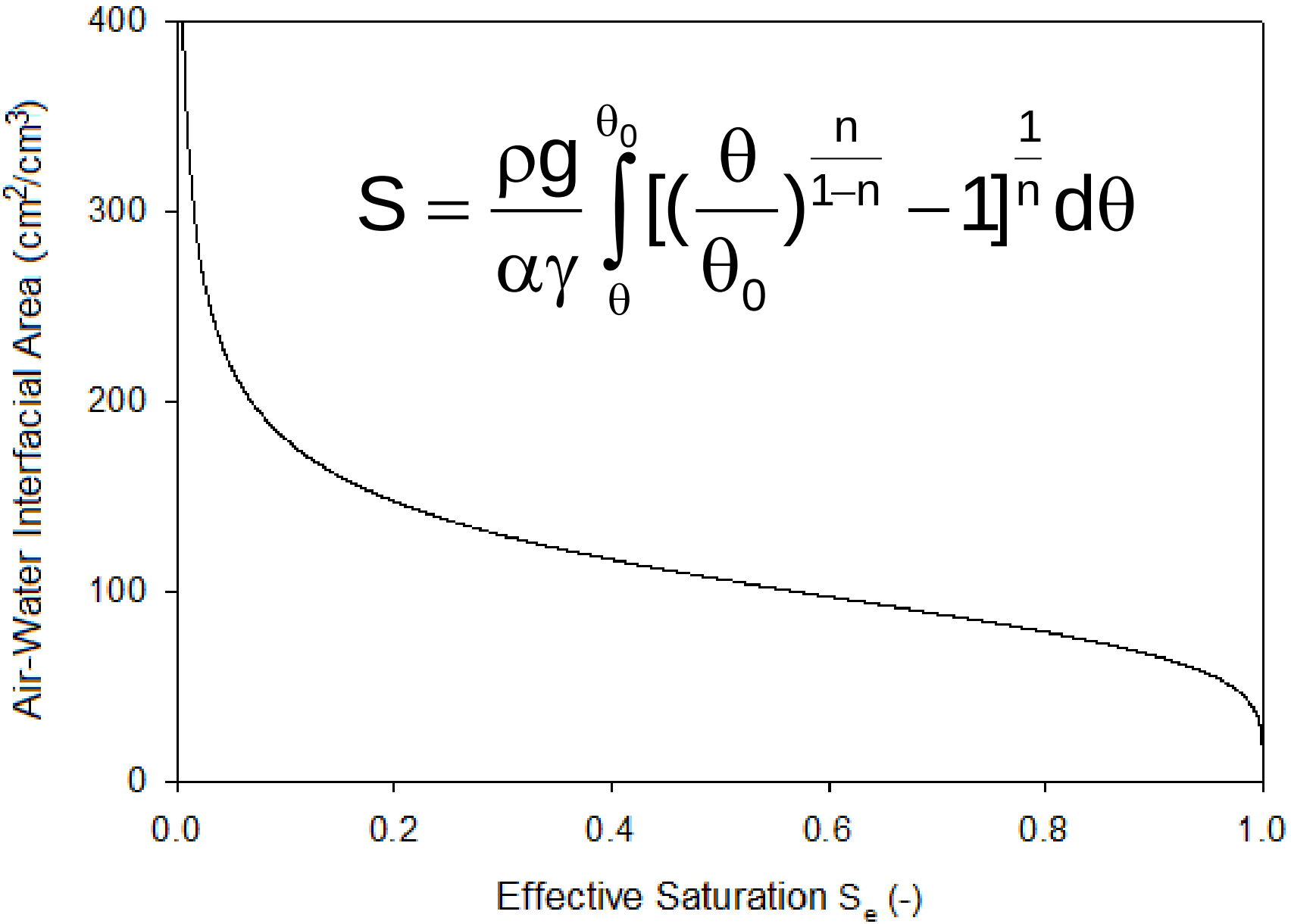
Bacterial Breakthrough Curve



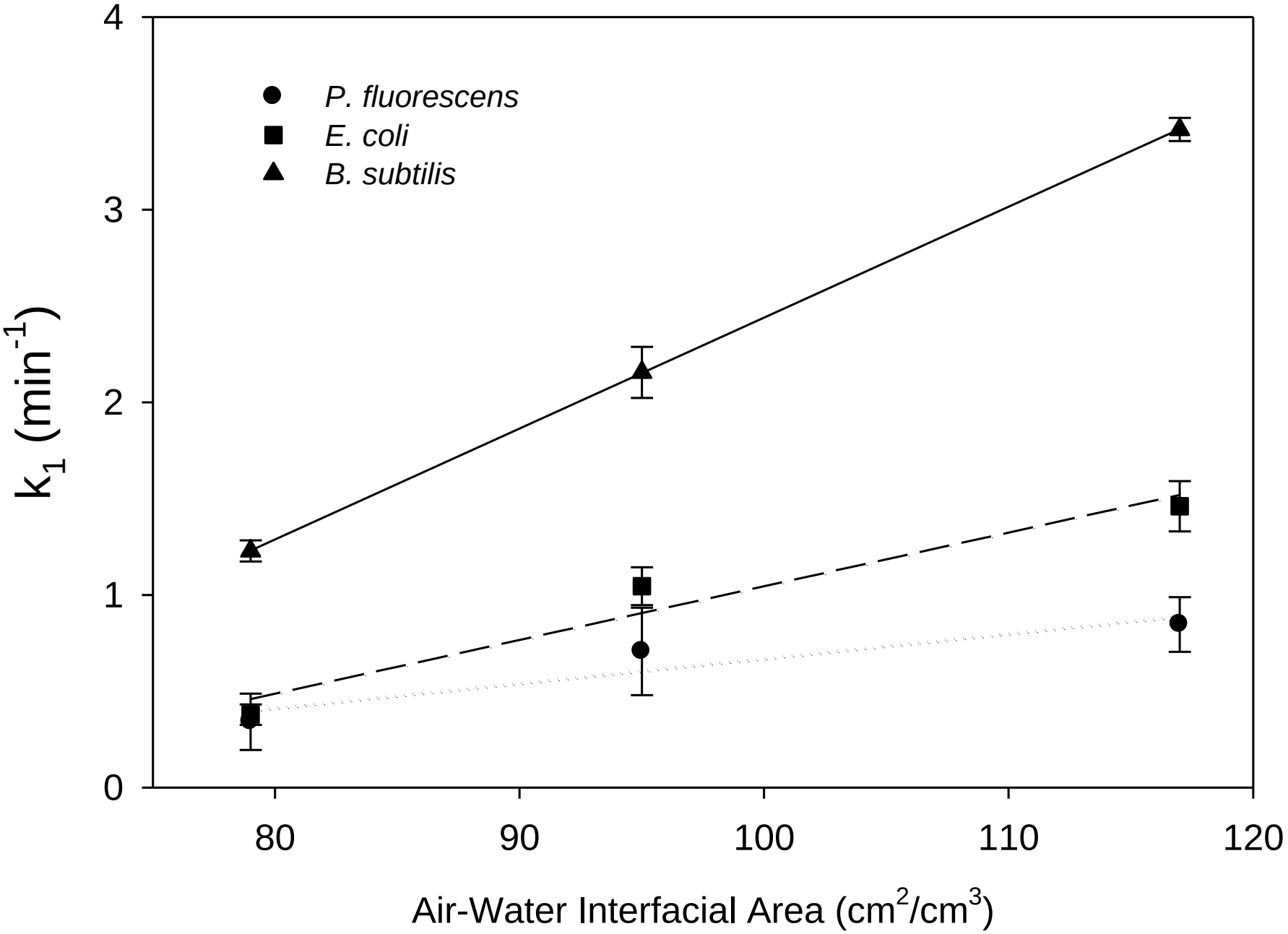
Deposition and Bacterial Interactions



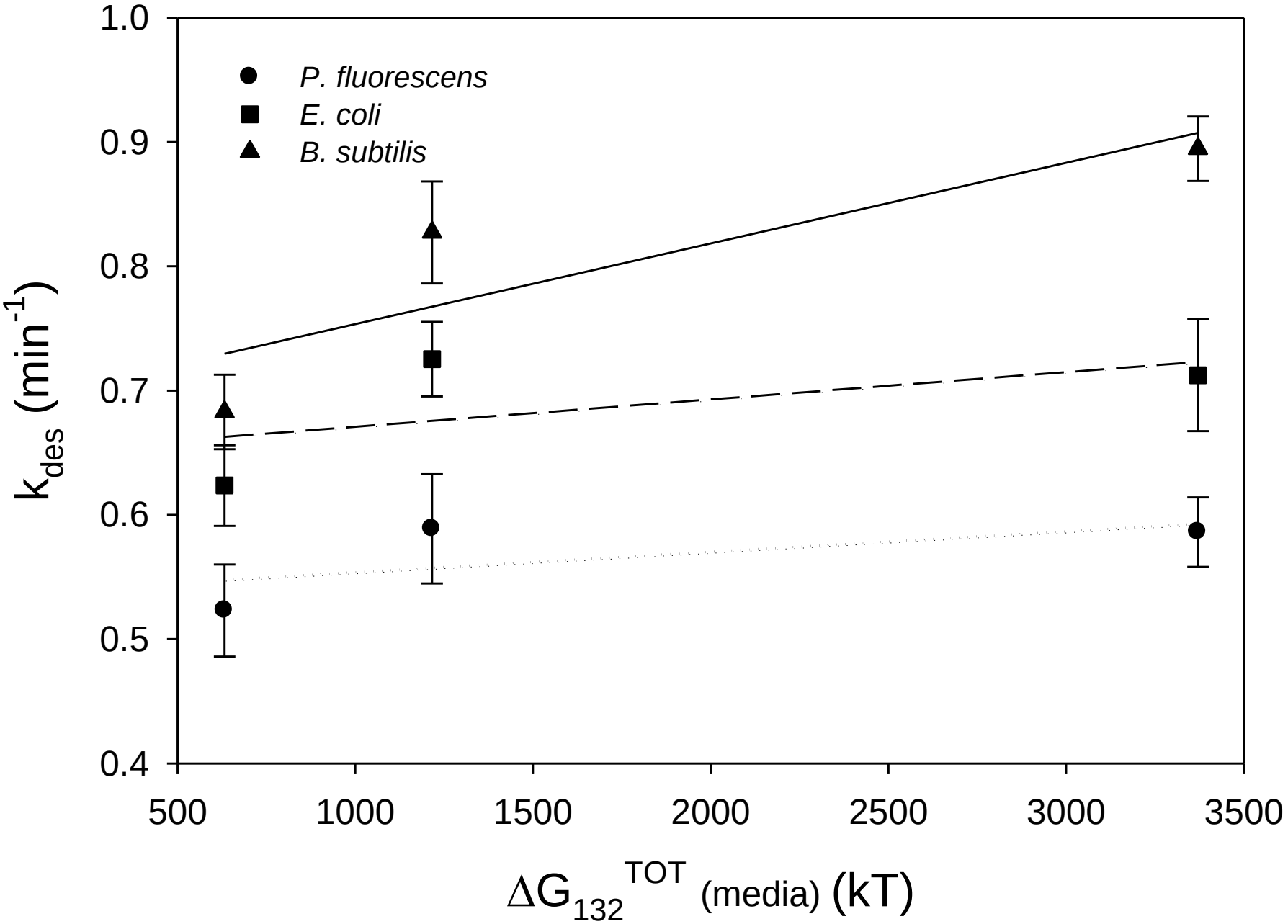
Air-Water Interfacial Area



Deposition and Interfacial Area



Desorption and Bacterial Interactions



Acknowledgements

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Questions?