

Bacterial Interactions and Transport in Unsaturated Porous Media

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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**

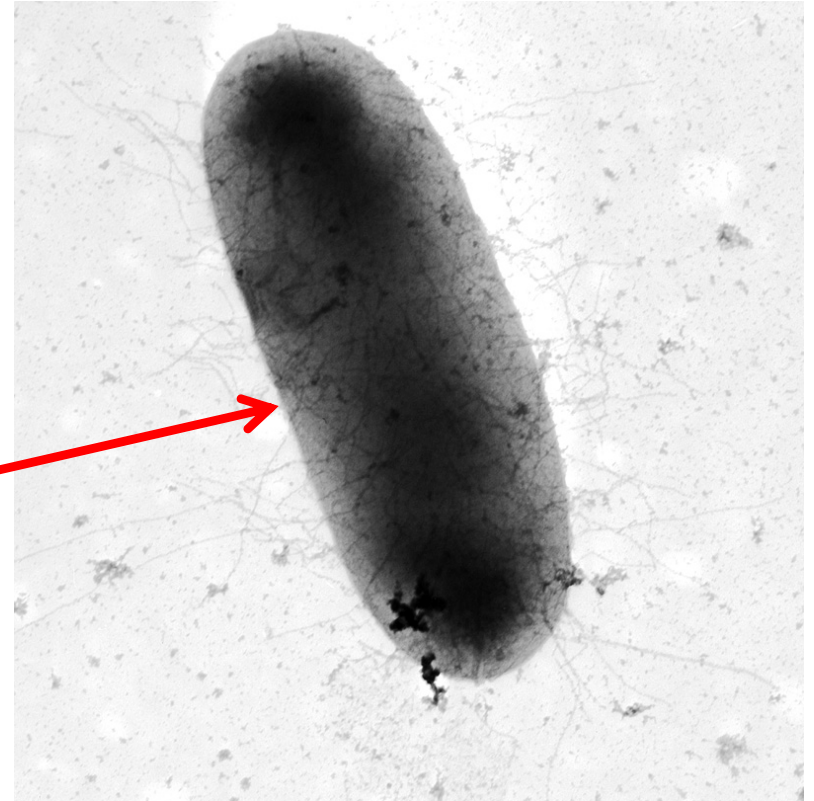
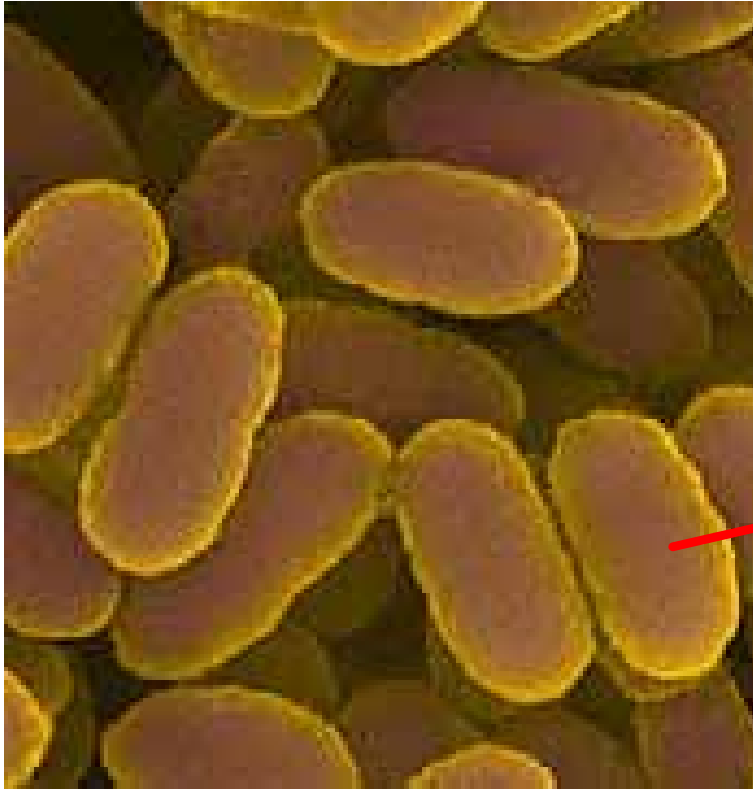


Objectives

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



Bacterial Strain

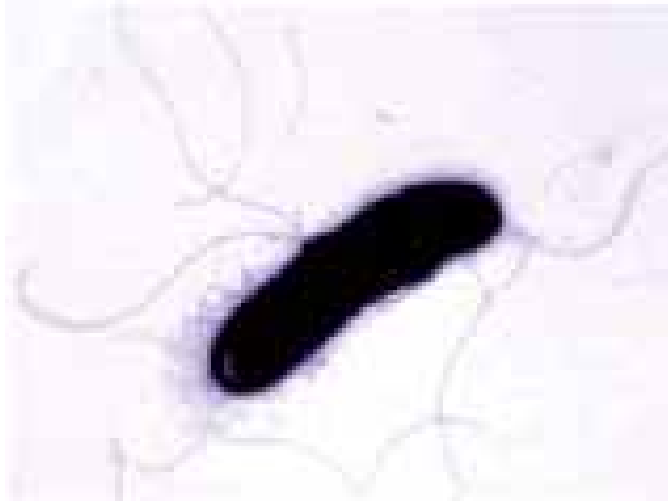


E. Coli HB101

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/m²)

γ^+ – Electron-acceptor parameter of Lewis acid/base component surface tension (mJ/m²)

γ^- – Electron-donor parameter of Lewis acid/base component surface tension (mJ/m²)

ζ – Zeta potential (mV)



van Oss-Chaudhury-Good Equation

Solve for γ_S^{LW} , γ_S^+ and γ_S^-

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

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



Interaction Free Energy Calculation

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

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

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

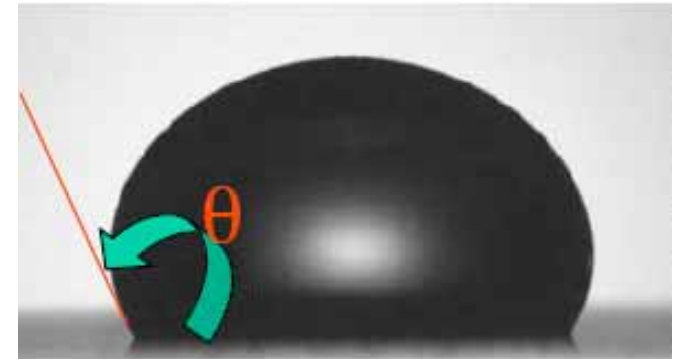
$$\Delta G(y)_{132}^{\text{EL}} = \pi \epsilon \epsilon_0 R [2\psi_1 \psi_2 \text{Ln}(\frac{1+e^{-ky}}{1-e^{-ky}}) + (\psi_1^2 + \psi_2^2) \text{Ln}(1-e^{-2ky})]$$



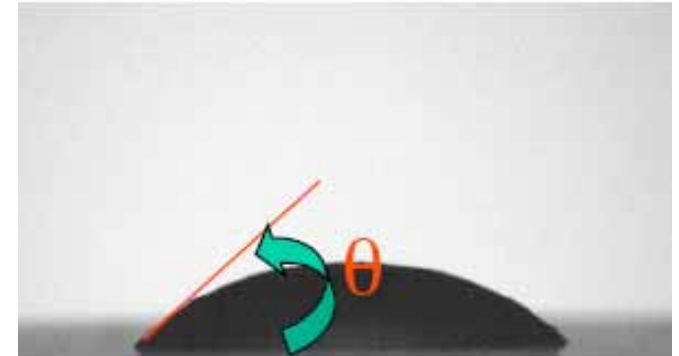
Contact Angle Measurement



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



Contact Angle $> 90^\circ$



Contact Angle $< 90^\circ$



Wicking Method



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)

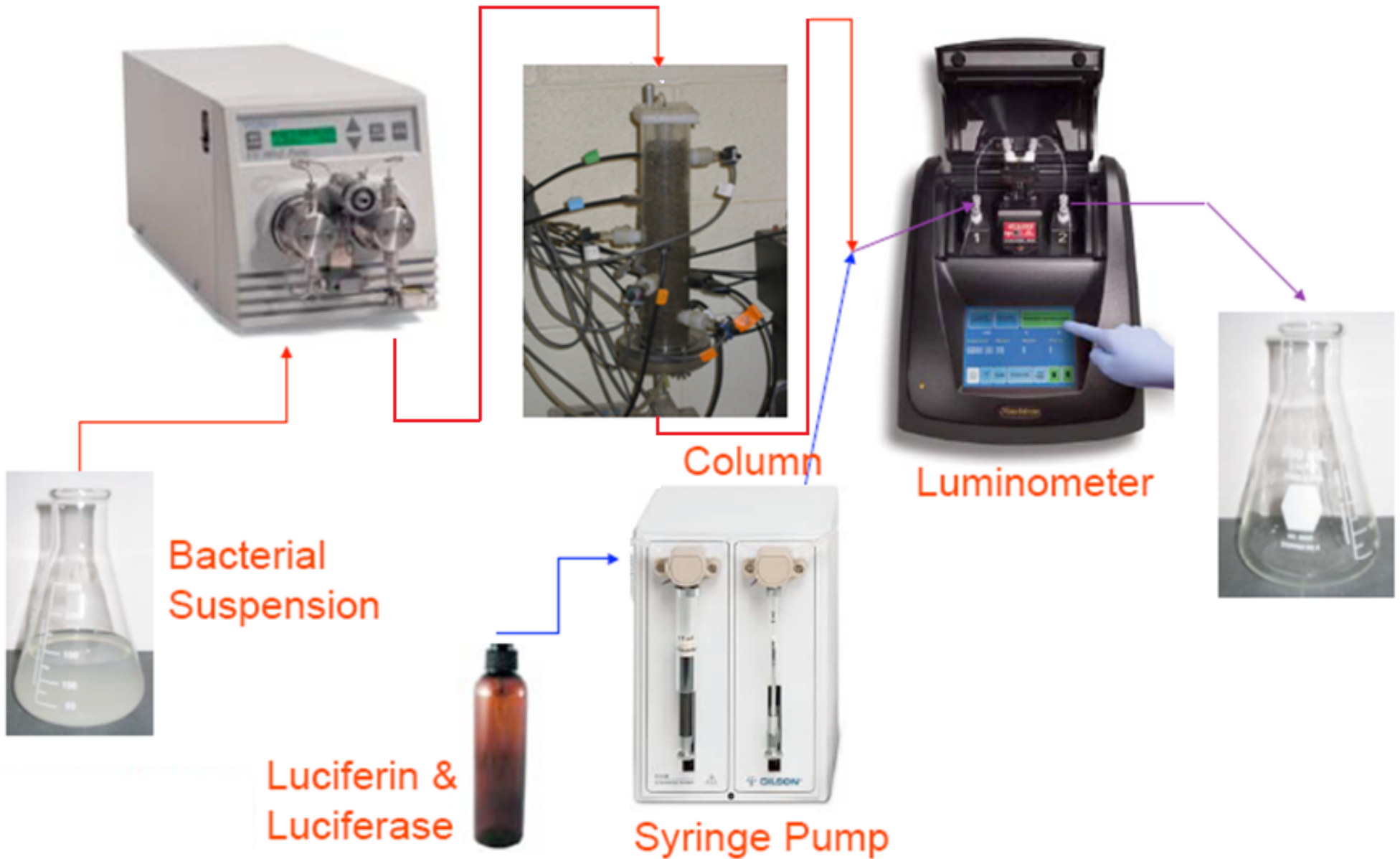
γ_L : Measuring liquid surface tension (mJ/m²)

μ : measuring liquid viscosity (N·s/m²)

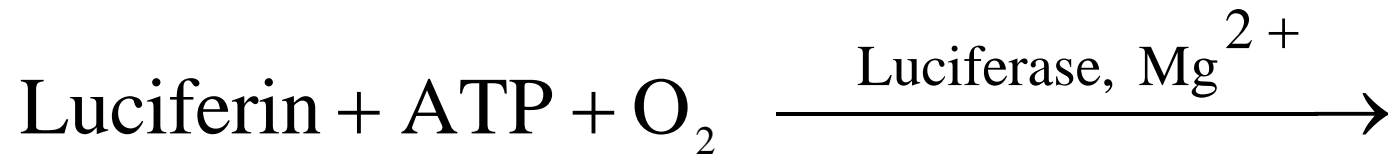
**Kruss K100
Tensiometer**



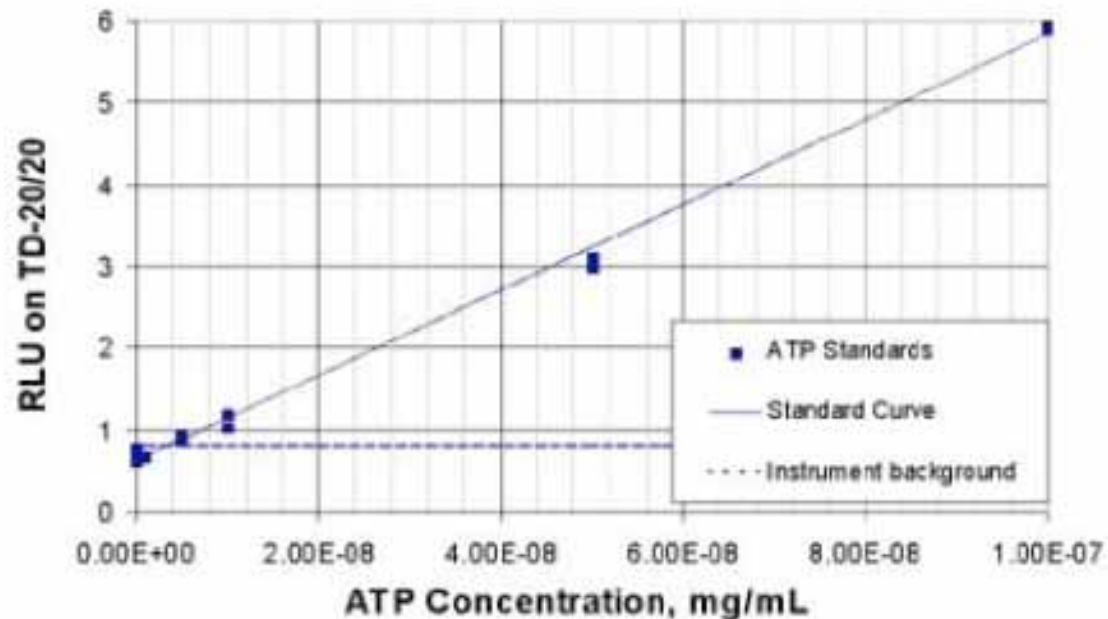
Column Experiment



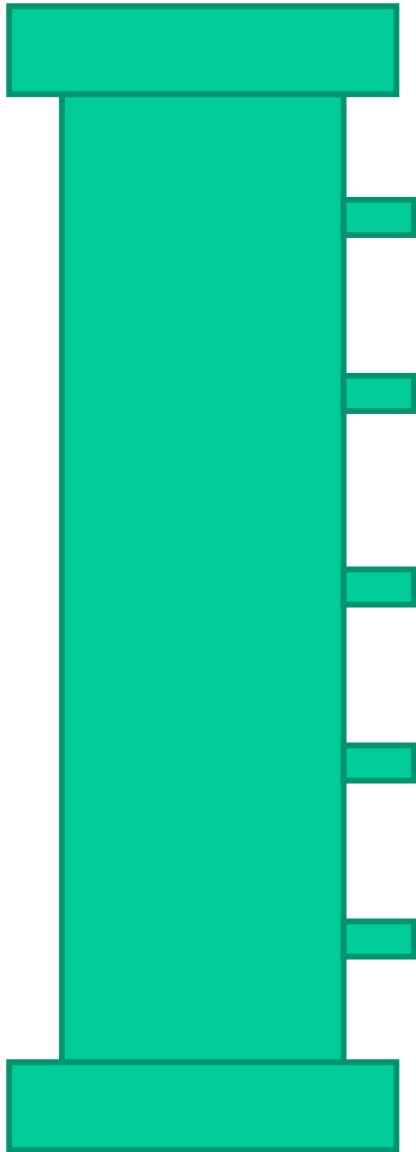
ATP Measurement



Oxyluciferin + AMP + CO₂ + PP_i + 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 (-)

$$\alpha = 0.136 \text{ cm}^{-1}$$

$$n = 4.776$$



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/m³)

C_r — retained bacterial concentration [cells/(g)(m²/m³)]

D_z — apparent dispersion coefficient (m²/sec)

θ_m — moisture content (m³/m³)

q — specific discharge (Darcian fluid flux) (m/sec)

k_1 — deposition coefficient (sec⁻¹)

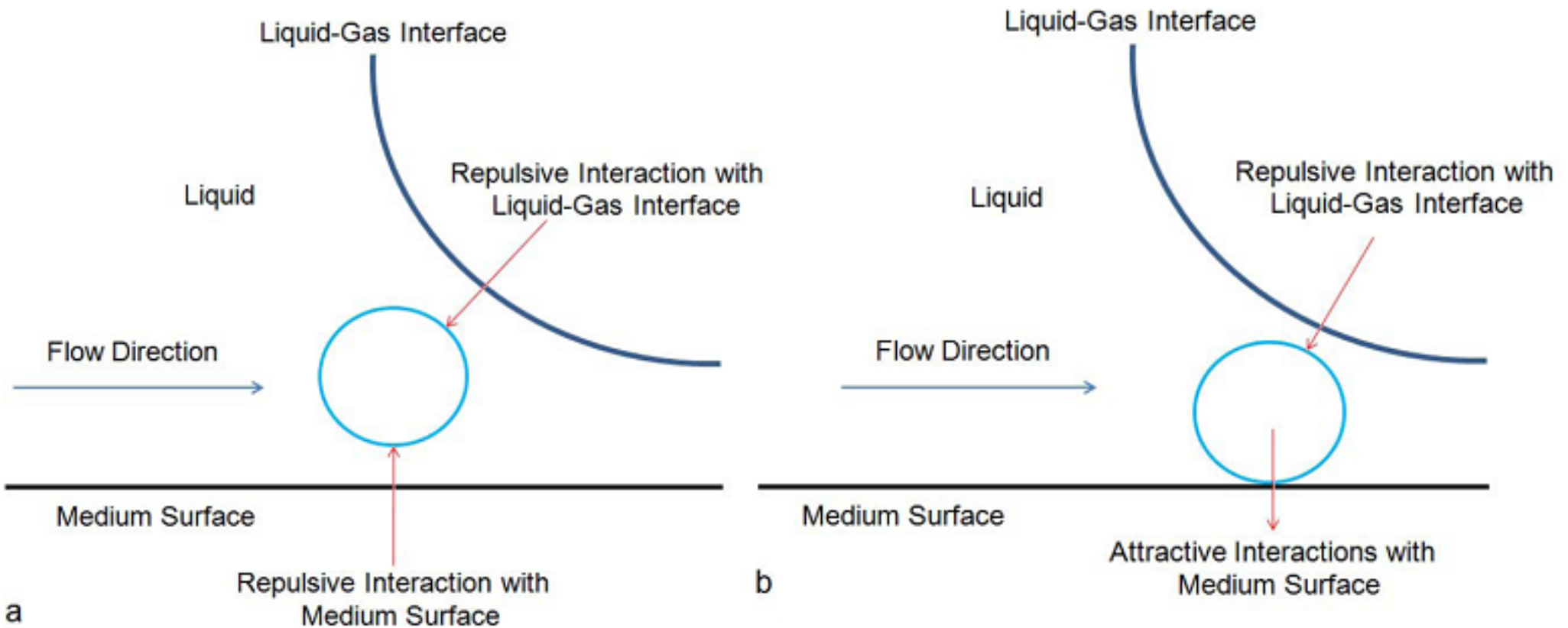
k_{des} — desorption coefficient (sec⁻¹)

ρ_b — bulk density (g/m³)

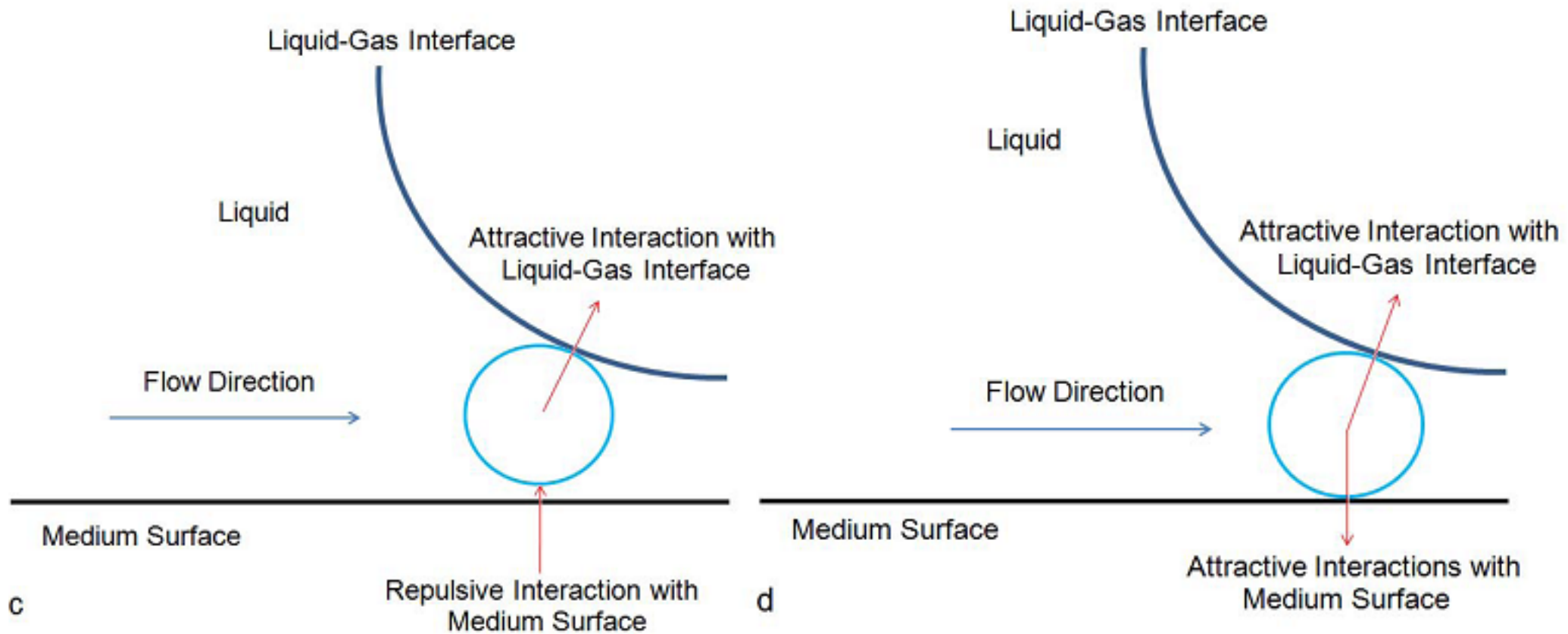
S — air-water interfacial area (m²/m³)



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)
<i>E. coli</i>	-36.3	1234.8	17.8	1216.3
<i>P. fluorescens</i>	-17.6	649.6	0.48	632.5
<i>B. subtilis</i>	-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, $1 \text{ kT} = 4.11 \times 10^{-21}$ 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)
<i>E. coli</i>	-7146.9	-3030.0	1481.1	-8695.8
<i>P. fluorescens</i>	-4080.2	-1726.5	917.3	-4889.4
<i>B. subtilis</i>	-19845.9	-6740.9	2611.6	-23975.2

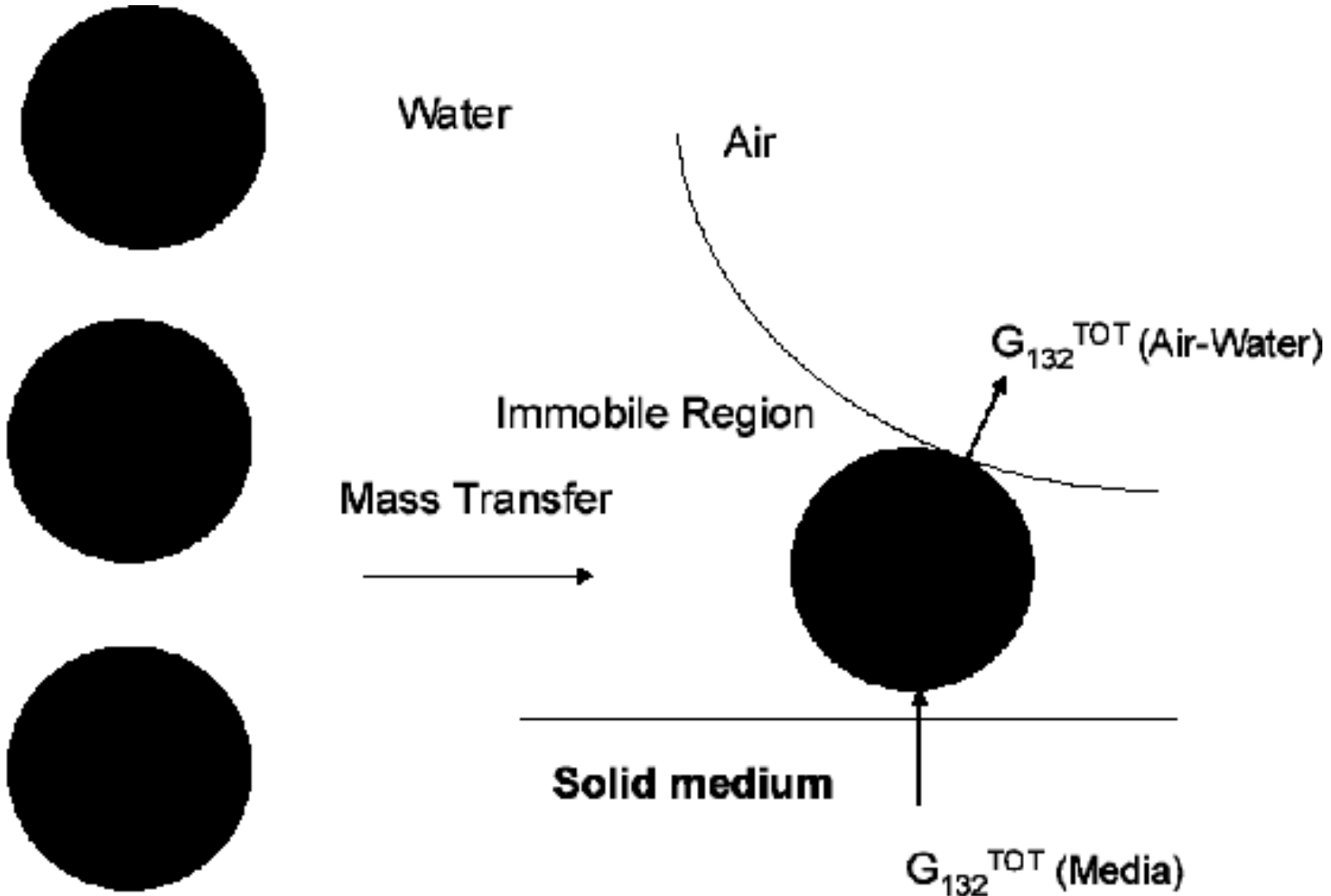
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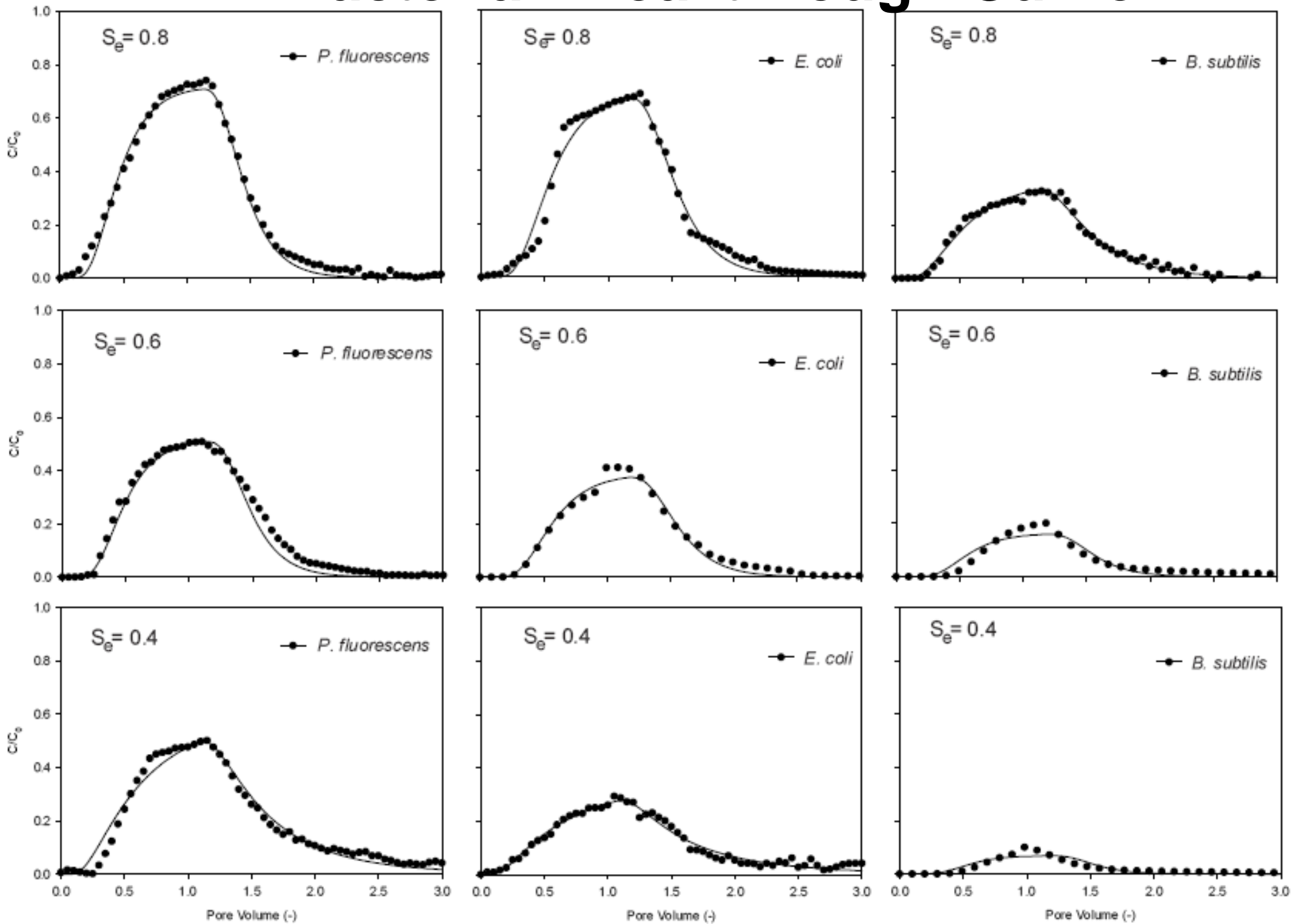
Bacterial Retention Mechanism



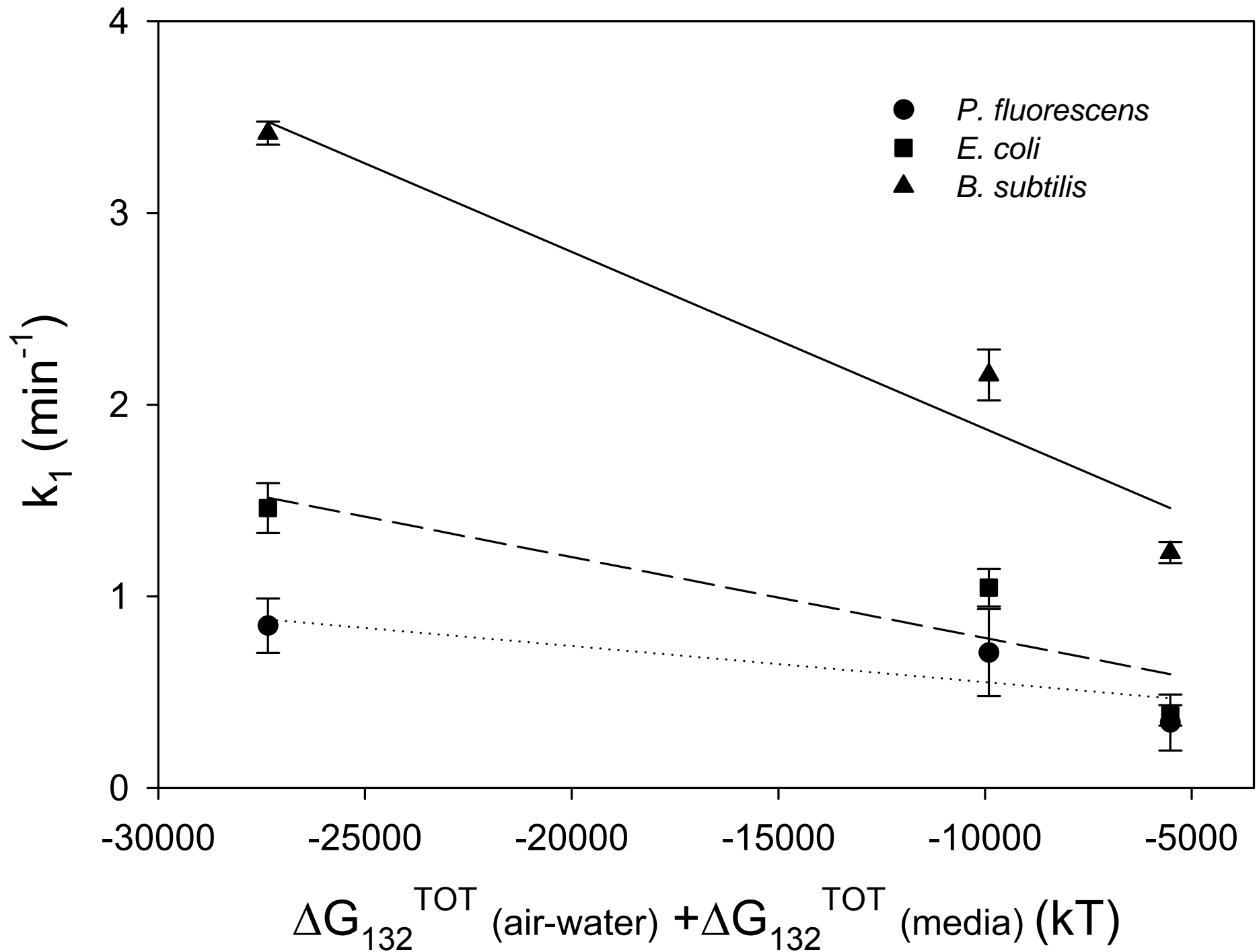
Mobile Region



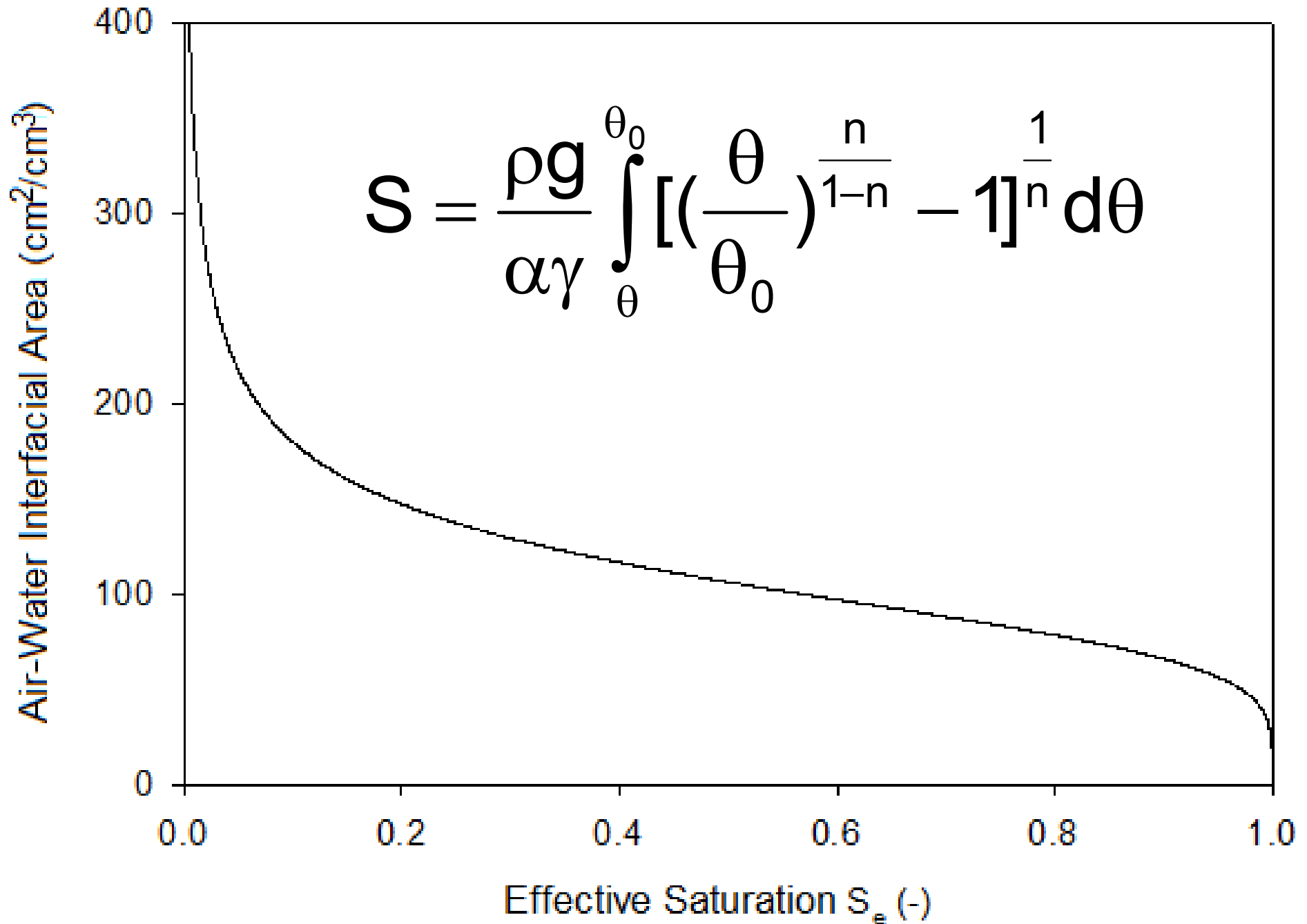
Bacterial Breakthrough Curve



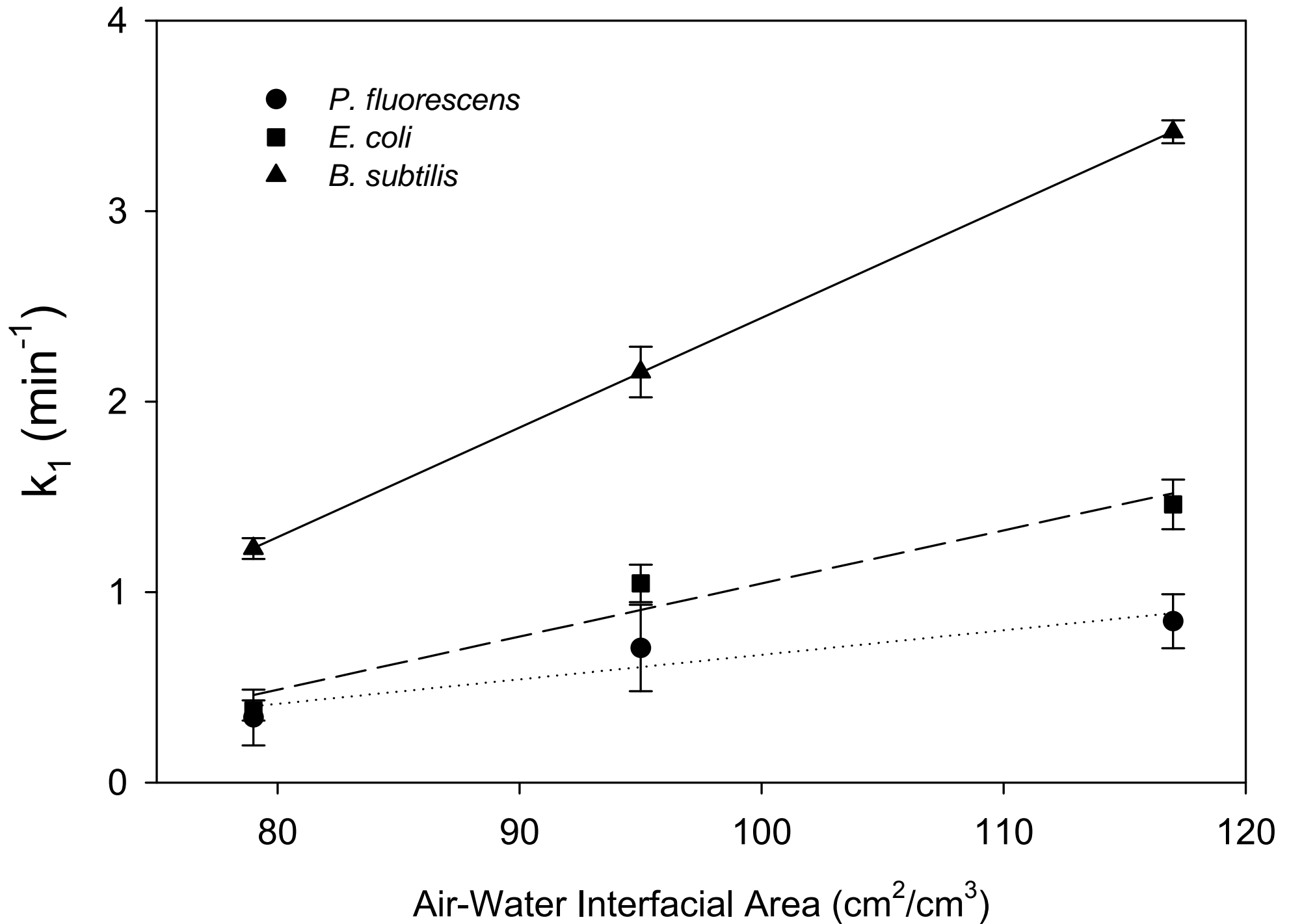
Deposition and Bacterial Interactions



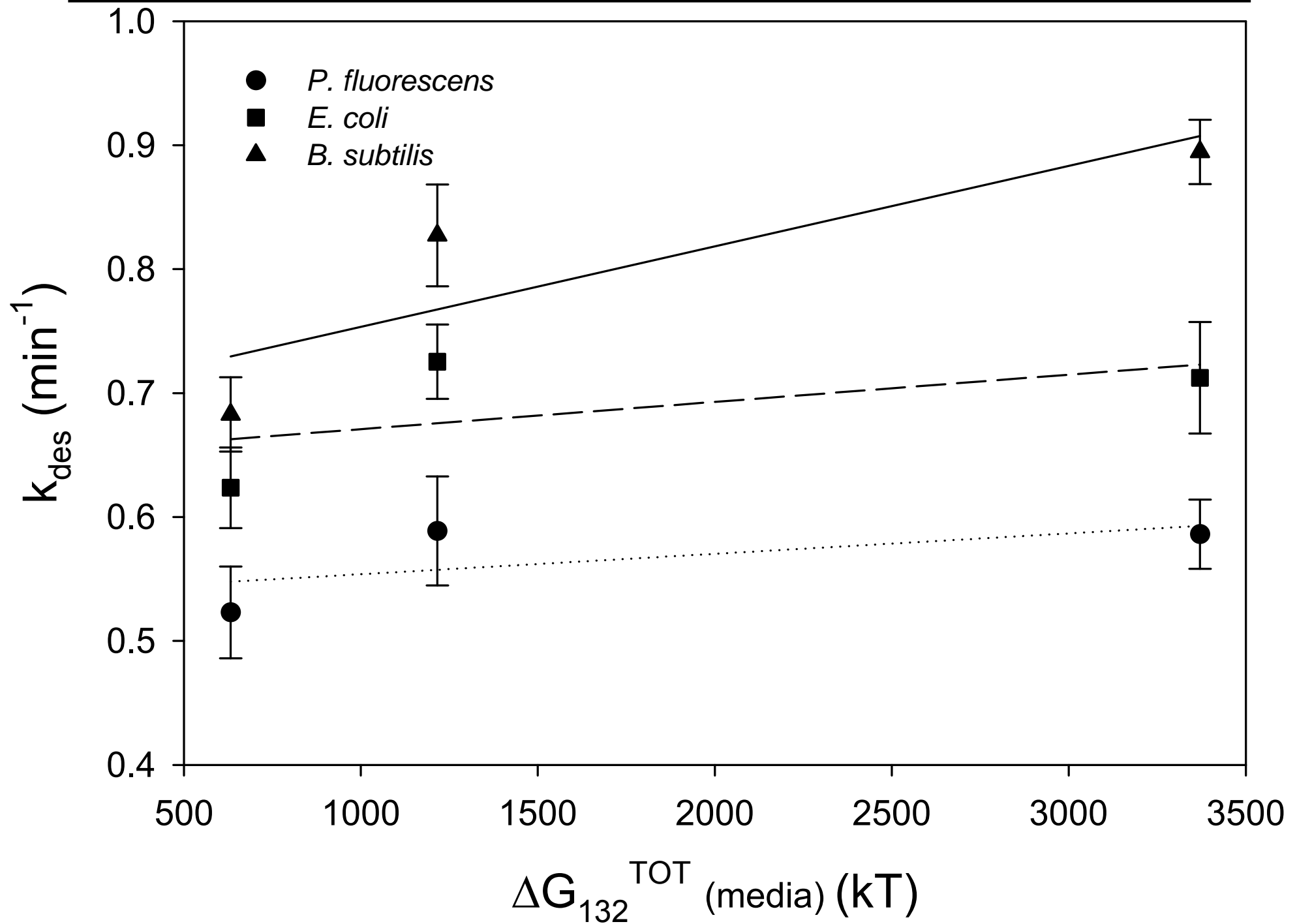
Air-Water Interfacial Area



Deposition and Interfacial Area



Desorption and Bacterial Interactions



Acknowledgements

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Questions?

