Modeling Transport of Antimicrobials Encapsulated in Yeast Microparticles for Biofilm Inactivation

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INTRODUCTION

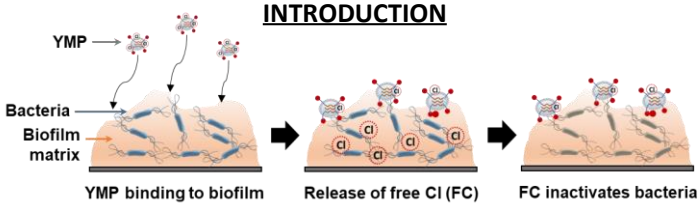

Figure 1. Transport processes of FC by using YMPs for biofilm inactivation

- Biofilms persist in various environments due to their protective matrix that neutralizes antimicrobials [1,2].
- The specific affinity of bio-based carriers can promote biofilm inactivation by targeted delivery of antimicrobials [3].
- Transport phenomena including reaction kinetics can predict the improved inactivation of biofilms using bio-carriers.

FC: free chlorine (antimicrobial) **YMP:** yeast microparticle (bio-carrier)

COMPUTATIONAL METHODS

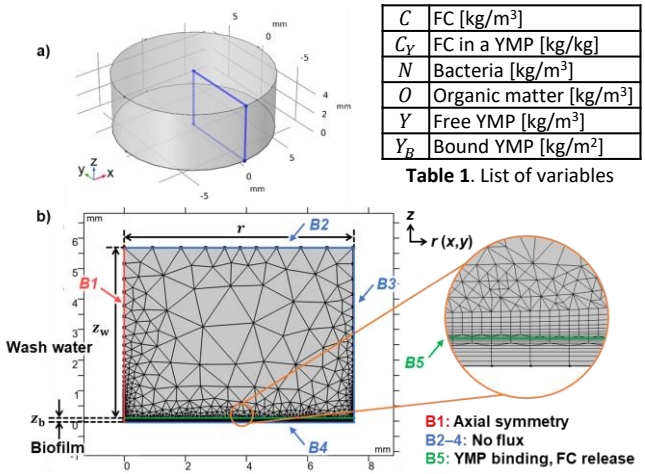

Figure 2. A biofilm inactivation system in laboratory settings: (a) 3D geometry, (b) radial cross-section with boundary conditions

C	FC [kg/m^3]
C_Y	FC in a YMP [kg/kg]
N	Bacteria [kg/m^3]
O	Organic matter [kg/m^3]
Y	Free YMP [kg/m^3]
Y_B	Bound YMP [kg/m^2]

Table 1. List of variables

Governing Equations

Wash water

$$\begin{cases} \textbf{FC: } \dfrac{\partial C}{\partial t} = D_C \nabla^2 C - k_0 C - k_1 O C \\ \textbf{YMP: } \dfrac{\partial Y}{\partial t} = D_Y \nabla^2 Y \end{cases}$$

Biofilm (porous)

$$\begin{cases} \textbf{FC: } \dfrac{\partial C}{\partial t} = \dfrac{1}{\phi} D_{C,\text{eff}} \nabla^2 C - k_0 C - k_1 (N+O) C \\ \quad D_{C,\text{eff}} = \left(\dfrac{\phi}{\tau}\right) D_C,\ \tau = \phi^{-1/3} \\ \textbf{Bacteria: } \dfrac{\partial N}{\partial t} = -k_2 N C \\ \textbf{Biofilm matrix: } \dfrac{\partial O}{\partial t} = k_2 N C \end{cases}$$

B5 Boundary Conditions

FC: $C = \left[Y_B \left(C_{Y,0} - C_Y\right)\right] \times \dfrac{A}{V}$

Y_B **measured by YMP binding to biofilm**

$$\begin{cases} \text{Free: } \dfrac{\partial Y}{\partial t} = \left[-k_b Y_{B,\infty} e^{-k_b t}\right] \times \dfrac{A}{V} \\ \text{Bound: } \dfrac{\partial Y_B}{\partial t} = k_b Y_{B,\infty} e^{-k_b t} \end{cases}$$

C_Y **measured by FC release from YMP**

$$\left\{\text{FC in YMP: } \frac{\partial C_Y}{\partial t} = -k_{r2} C_{Y,0} e^{-k_{r2} t}\right.$$

	Value	Units
k_0	2.88e-5	s^{-1}
k_1	8.97e-3	m^{3}kg^{-1}s^{-1}
k_2	12.5	m^{3}kg^{-1}s^{-1}
k_b	4.40e-4	s^{-1}
k_{r1}	1.06e-5	s^{-1}
k_{r2}	4.13e-3	s^{-1}

Table 2. Reaction rate parameters

RESULTS

- FC was rapidly depleted (→ 0) by organic-rich wash water but the use of YMPs reduced FC loss, increasing the contact time with target bacteria.

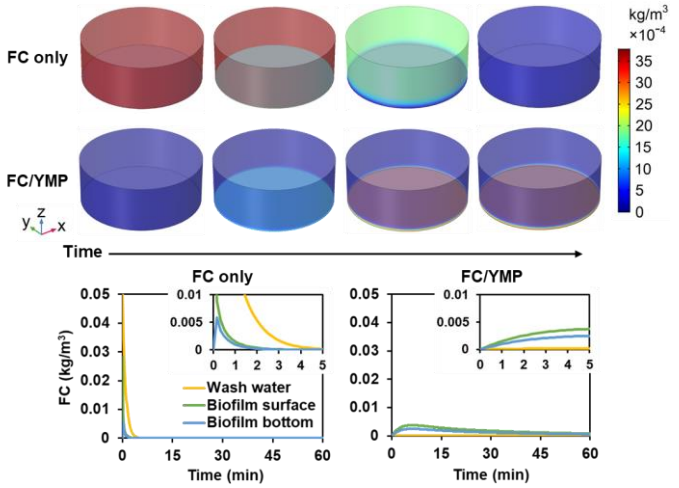

Figure 3. Simulated spatiotemporal FC distribution for each system

- 5.5 log CFU/ml bacteria survived in **FC only** model after 1 h while the biofilm was completely inactivated within 10 min in **FC/YMP** model.

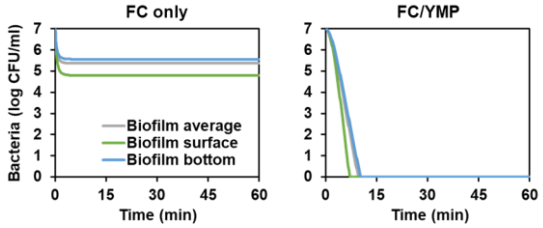

Figure 4. Simulated biofilm inactivation at different locations for each system

- The affinity of YMPs for binding biofilms was a dominant factor to improve the inactivation of bacteria in biofilms.
- The simulated biofilm inactivation was experimentally validated by using two types of YMPs with different binding affinities.

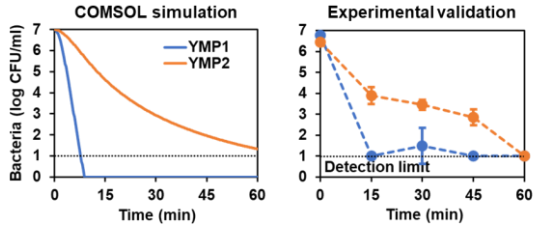

Figure 5. Experimental validation: Biofilm inactivation by FC encapsulated in two types of YMPs with different binding affinities

CONCLUSIONS

- The binding affinity of bio-carriers to a biofilm increased the local mass transfer of antimicrobials into the biofilm.
- Controlled release of antimicrobials from bio-carriers reduced nonspecific reactions with organic matter in the wash water.
- Overall, this study illustrates the potential of a multiphysics modeling approach to enable the rational design of antimicrobial delivery systems for the treatment of biofilms.

REFERENCES

1. Yadav et al., Microbial biofilms and human disease: A concise review, *New and Future Developments in Microbial Biotechnology and Bioengineering: Microbial Biofilms*, 1–13 (2020)
2. Hall-Stoodley et al., Bacterial biofilms: From the natural environment to infectious diseases, *Nat. Rev. Microbiol.*, 2, 95–108 (2004)
3. Huang et al., Biobased sanitizer delivery system for improved sanitation of bacterial and fungal biofilms, ACS Appl. Mater. Interfaces, 11, 17204–17214 (2019)

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