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Modeling phototrophic biofilm growth: The role of phototaxis in microbial ecology

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Biofilms are complex microbial communities that adhere to surfaces and are encased in a self-produced matrix of extracellular polymeric substances (EPS). These ecosystems constantly evolve in response to environmental fluctuations, and exhibit intricate dynamics governed by interconnected mechanisms. The motility of microorganisms within biofilms is crucial, as it directly affects the biofilm's spatial organization, composition, and overall development. Among the motility mechanisms, phototaxis plays a pivotal role by enabling microorganisms to move in response to light, guiding the positioning of planktonic cells within the biofilm matrix. This movement optimizes light exposure, enhancing beneficial conditions while avoiding harmful intensities. As a result, phototaxis influences microbial spatial distribution, metabolic cooperation, and ecological adaptation within the biofilm.

In this study, a mathematical model that explores the role of phototaxis in biofilm growth and organization is presented. The proposed model is formulated as a hyperbolic-parabolic free boundary value problem, where the biofilm is modeled as a homogeneous, viscous, incompressible fluid with velocity governed by Darcy's law. It considers two state variables representing the planktonic and sessile phenotypes and reproduces the transition from one state to the other. Additionally, two different planktonic cells motion behaviours are considered: random motility governed by the diffusion process, and directional motility driven by phototactic responses to light gradients. A light-dependent sensitivity function captures both positive and negative phototaxis.

Numerical simulations analyze biofilm evolution under biologically relevant conditions and examine the impact of phototaxis on biofilm dynamics and ecology. The distribution of phototrophic biomass emerges from the interaction between random diffusion and phototactic movement. The results indicate that

motile cells accumulate in regions with optimal light, stimulating the growth of sessile phototrophic cells and facilitating biofilm development.

Keywords: biofilm, phototaxis, free boundary value problem, numerical simulations