Can We Select Desired Microbial Collectives? Answers from Statistical Physics

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Microbial collectives can perform complex functions — such as waste degradation, probiotic activity, and nutrient synthesis — that no single member species could achieve alone. Engineering such collectives through artificial selection holds great promise, yet the conditions under which selection succeeds or fails remain poorly understood.

The growth and death of microbial cells can be understood as a reaction scheme, a stochastic dynamics for which physics provides well-developed analytical tools. Thus, we use these tools to study collective selection. In our earlier work [1], we modeled collectives comprising slow- and fast-growing subpopulations undergoing repeated maturation-selection-reproduction cycles. Using Gaussian approximations and extreme value theory, we derived analytical conditions for selection success and showed that achievable target compositions depend critically on both the target and the initial collective composition.

Building on this foundation, we recently developed a more general and unified theoretical framework [2]. The selection protocol involves two dynamic timescales — bacterial doubling time and maturation duration — whose interplay maps naturally onto the mathematics of stochastic resetting. We treat the collective state as an effective particle evolving in a potential landscape, with resetting events governed by the group's extreme values. Via renewal theory and a Fokker-Planck formulation, this framework yields closed-form expressions for stationary distributions, capturing the long-time behavior of iterative selection dynamics in a transparent and analytically tractable way. Beyond microbial collectives, the framework applies broadly to group-resetting processes, as we demonstrate through an application to collective avoidance behavior. Together, these results offer a principled theoretical language for understanding and designing artificial selection protocols for microbial collectives.

[1] J. Lee, W. Shou, H. J. Park, eLife 13, RP97461 (2025).
[2] J. Lee, S.-G. Yang, H. J. Park, L. Lizana, Phys. Rev. Research 8, 013227 (2026).