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Prof. Staffan Kjelleberg is Director of the Singapore Centre on Environmental Life Sciences Engineering, NTU Singapore, and Co-Director, the Centre for Marine Bio-Innovation UNSW Australia. His research interests include bacterial biofilm biology, chemically mediated interactions used by bacteria and higher organisms, and harnessing/controlling biofilms for engineering and public health applications. His research incorporates a meta-'omics approach to explore microbial communities and processes in complex systems, with translational outcomes in biotechnology and environmental/public health domains.

Kjelleberg has employed a multidisciplinary approach for advancements in microbial ecology, as well as for the merger of the previously disparate fields of environmental microbiology, eukaryote ecology and environmental engineering. His work on bacterial adaptive responses and biofilm biology has provided insights into the predominant modes of life of bacteria in the environment. Discoveries of interactions at different scales, ranging from within the biofilm, between biofilms and their surrounding environment, to those with higher organisms, have contributed to ecological theory and biofilm control outcomes.

Microbial Biofilms - A Highly Complex Default Mode of Life

The largest biomass and highest activity on the planet rest with microorganisms. These are extraordinarily diverse both functionally and phylogenetically (as different as elephants and roses). As a default, microorganisms operate in highly organised biofilm assemblages, with the outcome being more than the sum of the individual members.

While there is progress in scrutinising the identity of microbial members within biofilms, in most habitats – whether natural or manmade – the extent of their diversity is only beginning to be understood.

However, while essential, the emergent properties of biofilms cannot be predicted by the characteristics of individual members only, but rather, we need to understand the organisation in which they live, i.e. the biofilm. What we see is a complex development program involving intricate and highly organised architecture that allows the structure to drive communal biofilm functions. This involves the highly sophisticated extracellular matrix – the structural scaffold of a microbial biofilm that has building blocks with both

structural and functional roles. For example, exopolysaccharides regulate biofilm rheology as well as provide electroconductivity highways, and filamentous phage regulate developmental cycles as well ensure structural stability.

Just as a city revolves around the effective functioning of its components, a biofilm uses its organisation for coordinated and highly regulated networks. These include multiple cellular communication systems and co-metabolism across organisms with strikingly different physiologies. This imparts unique traits such as mechanisms for protection (accounting for the inefficacy of antibiotics against biofilm infections), altruism, energy transfer, waste-management and resource utilisation.

Our initial understanding of such biofilm structures and functions is based on relatively simple single species (population) models, which are themselves, already remarkably complex. Yet the challenge is to arrive at an understanding of the coordinated networks that are essential for the diverse multi-species biofilm communities that predominate in all habitats.

Technological advancements such as high-resolution next generation sequencing are facilitating inroads into this next frontier to understanding complexity at systems level. Specifically, we can now analyse cell-cell interactions between species and across kingdoms and map the complex communal metabolic networks that are required for ecosystem functioning in highly diverse biofilms.

These advancements provide the opportunity to unravel the previously undocumented intricacies of biofilms. Biofilm science will thus increasingly require a complex systems approach to understand microorganisms - the largest and most influential biological entity on the planet.