Mechanobiological Manufacturing of Functional Products

The proposed Blue Sky idea is about the mechanobiological manufacturing of functional products by integrating engineering production approaches and microorganism-based metabolic activities to achieve environmental consciousness in making nature-like products with advanced functionalities. Engineering production approaches are first utilized to manufacture preliminary patterns as green structures, which are further processed directly by microorganisms to transform themselves into functional products or serve as microenvironments for microorganisms to produce novel products.

Specifically, the process includes some or all of the following three sequential steps: 1) preparation of three-dimensional (3D) guidance cue-rich green structures using applicable manufacturing technologies such as 3D printing, 2) selective inoculation or printing of applicable microorganisms into each green structure, and 3) cellular manufacturing of functional products by converting green structures into final products under the assistance of microorganisms or secreting of final materials from microorganisms by using green structures as factory microenvironment. The former is referred to as direct mechanobiological manufacturing, and the latter is indirect mechanobiological manufacturing. For both, each microorganism functions as a worker in a physical factory. The general concept can be illustrated with a representative implementation of direct mechanobiological manufacturing by utilizing the unique biomineralization capacity of microorganisms to manufacture strong, self-healing, and mineralized products. Inorganic minerals such as calcium carbonate ($CaCO_3$) can be deposited via urease released from select bacterial strains including *Sporosarcina pasteurii*. This approach can be applied to print $CaCO_3$ (the main constituent of corals) for the important yet challenging application of coral reef restoration. Briefly, the proposed approach first prints porous coral skeletons from biodegradable polymers such as polylactic acid (PLA). Then it uses *S. pasteurii* to catalyze urea hydrolysis for the production of ammonia and carbon dioxide. The latter reacts with water to form carbonate ions, which react with calcium cations present in the environment to form $CaCO_3$ in the pores and on the surface of porous skeletons, resulting in PLA-$CaCO_3$ structures for coral microfragment seeding and larva recruitment. Finally, PLA degrades after PLA-$CaCO_3$ structures are outplanted on a marine bottom for environmental recovery and protection.

The direct mechanobiological manufacturing approach can also be implemented to address other grand challenges. For example, it can promote a low-carbon economy when it comes to 3D printing for construction. Current cement production accounts for 8% of CO2 emissions. The proposed approach can help maintain a near-zero carbon footprint in printing concrete structures while resulting in stronger and lighter structures than typical concrete masonry. Specifically, a bacteria/sand-based biocement can be designed and printed into gravel structures, via producing crystal-forming $CaCO_3$, to replace conventional cement. This approach may find diverse applications ranging from sustainable self-healing built environments to space construction via *in-situ* resource utilization.

Similarly, the indirect mechanobiological manufacturing approach opens up opportunities for the production of many functional products from hydrocarbons using photosynthesis devices to vaccines and medicines such as penicillin using artificial pharmaceutical factories with microorganisms as diligent workers to fabricate structures. The list of such functional products, manufactured either directly or indirectly, will continue to diversify and grow in the future.