Controlling Reaction-Diffusion Mechanisms for Advanced Self-Assembled Architectures: Periodic Precipitation and Chemical Gardens

Abstract for the general public

Nature's remarkable ability to form intricate structures, such as Liesegang rings in mineral patterns or plant-like tubes found at hydrothermal vents, offers a fascinating source of inspiration for scientists. These natural phenomena result from processes where chemical reactions and material transport combine to create complex patterns and architectures. This project seeks to replicate these processes using reaction-diffusion (RD) systems, which involve chemical reactions coupled with the controlled diffusion of substances. By harnessing these mechanisms, the research aims to develop self-assembled materials with advanced structures, such as hierarchical two-dimensional (2D) patterns and tubular architectures, that could revolutionize various applications in science and technology.

The study focuses on two primary approaches: periodic precipitation and chemobrionics. Periodic precipitation mimics the natural formation of Liesegang rings, where regularly spaced layers or bands emerge as chemicals diffuse through a medium, such as a gel. These rings are a striking example of natural pattern formation, where reactants meet, exceed saturation thresholds, and precipitate in rhythmic intervals. By precisely adjusting factors like temperature, chemical concentration, or the porosity of the medium, the project aims to control the size, spacing, and arrangement of these patterns to create functional materials with tailored properties.

A classic example of such systems is chemical gardens. For instance, when a metal salt, such as cobalt chloride, is added to a sodium silicate solution, it dissolves and reacts to form insoluble cobalt silicate, which acts as a semipermeable membrane. Due to the higher ionic strength inside the membrane than the surrounding solution, osmotic pressure builds, eventually tearing the membrane and creating a hole. Cobalt cations react with silicate anions at the tear, forming new solids. This process leads to the growth of colorful, plant-like structures, with the color determined by the metal cation. The rise of such structures was observed, discovered, and published by Johann Glauber in "*Furni Novi Philosophici*" in the XVII century. Similar tubular structures are found in natural systems like hydrothermal vents on the ocean floor. These vents produce hollow, plant-like formations through chemical reactions driven by diffusion and pressure differences. By using reaction-diffusion processes, the project will create similar hollow tubular structures from advanced materials such as metal-organic frameworks (MOFs). MOFs are highly versatile materials with exceptional porosity and functionality, making them ideal for applications such as targeted drug delivery, gas storage, or catalysis.

One of the most groundbreaking aspects of this research is its focus on creating hybrid materials by integrating multiple components into a single RD system. This multiplexed approach will allow for the development of multicomponent structures with unique and diverse functionalities. These advanced materials could be used in areas like energy storage, environmental sensing, and catalytic processes, offering solutions to pressing global challenges.

In addition to its practical applications, the project aims to bridge the gap between the nanoscale properties of materials and their large-scale usability. It will explore how to control these processes with high precision, ensuring that the methods developed are scalable and reproducible for real-world implementation. The biomimetic nature of the study, drawing directly from natural processes, adds another dimension of innovation by bringing us closer to the creation of life-like, dynamic materials.

Ultimately, this research deepens our understanding of how natural patterns and structures are formed and applies this knowledge to develop materials with transformative potential. By combining the beauty of natural processes with cutting-edge technology, the project aims to drive forward advancements in nanotechnology, materials science, and beyond.