Hierarchically porous materials and green carbon science—an interview with Ming-Yuan He

By Li-Hua Chen

Many examples of hierarchies are present in nature, such as water transport in leaf vein systems, the respiratory system, the blood circulatory system, etc. Hierarchically structuring a material over different length scales by mimicking natural systems can provide an opportunity to render the material suitable for a variety of functions. Tremendous research over the past decade has focused on the synthesis and applications of hierarchically structured porous materials. This rapidly evolving field has attracted great interest from both academia and industry. China is at the forefront of this field, and a scientific leader of this research is Professor Ming-Yuan He of East China Normal University. Professor He was elected to the Chinese Academy of Sciences in 1995, and he received the Prize for Scientific and Technological Progress from the Ho Leung Ho Li Foundation in 2001. He also won the National Catalysis Achievement Award of China in 2012 and the National Zeolite Lifetime Achievement Award of China in 2019. Professor He’s research interests focus on new catalytic materials and oil-refining catalysts and processes. He is a pioneer in the area of green chemistry in China and actively promotes the development of green chemistry and chemical engineering.

NSR recently interviewed Professor He about the current achievements and future prospects of hierarchically structured porous materials. This interview is dedicated to Professor He on the occasion of his 80th birthday, in recognition of his distinguished contributions to many aspects in the field of catalytic science and technology.

NSR: Hierarchies are present in many places in our environment, such as in biological systems from simple unicellular organisms to the more complex human body. Could you please discuss the definition of porous hierarchy? What are hierarchically structured porous materials?

He: In a broad sense, multi-porous materials are those materials possessing pore structure with a bi- or multimodal pore size distribution, irrespective of whether or how these two (or more) different pore systems are interconnected. Bi- or multimodal porous systems can be specified as ‘hierarchical’ only if the overall pore system shows a well-ranked porous structure that increases mass transport. Thus, it should be noted that the term ‘hierarchically structured porous material’ is specifically used to draw a clear distinction between this type of material and the broader term ‘multi-porous material’.

In March 2017, Professor Bao-Lian Su, Professor Zai-Ku Xie, and I co-chaired the 590th Xiangshan Science Conference in Beijing. At this conference, hierarchically structured porous materials were defined as materials with a porous structure consisting of interconnected pores on different length scales including micropores (<2 nm), mesopores (2–50 nm) and macropores (>50 nm). In hierarchically structured porous materials, the micropores provide size and shape selectivity for guest molecules, the mesopores increase micropore accessibility, and the macropores provide unimpeded transport paths. This pore hierarchy is particularly important for the diffusion of large molecules or in viscous systems. In short, the criteria of hierarchically structured porous materials are multiple levels, interconnectivity and regularity.

NSR: Multiple fields ranging from biotechnology, biomedicine, catalysis, energy, optics, and separation to biomolecule immobilization and bio-organisms have a fervent interest in hierarchically structured porous materials. What do you think are some of the most important questions today in research on hierarchically structured porous materials?

He: I think that the first topic to address is the need to develop new synthesis strategies for the future design of
The essential factors regarding CO₂ and the green-house effect are therefore balance and recycling.

—Ming-Yuan He
energy will continue to be the dominant energy source in the foreseeable future. The highly efficient utilization of the limited petroleum resources is extremely important because we have no alternative sources and technologies to provide the tremendous amount of liquid transportation fuels we need at present. Designing hierarchically porous catalyst materials to minimize the generation of coke and CO₂ under industrial conditions is critical.

Hierarchically porous materials play an important role in many biomass conversion routes. Biomass provides a huge amount of renewable carbon. Efficient transformation of biomass into high-quality fuels and chemicals is a long-standing task. Typically, biomass conversion involves the decomposition of bulky biopolymers into small basic molecules and then often the further processing of these small molecules to form value-added end-products. The accelerated diffusion performance and improved accessibility to active sites achieved using hierarchically structured porous materials help to facilitate biomass conversion. Hierarchically structuring both the porosity and architecture of a material over different length scales provides the opportunity to render the material suitable for a variety of functions that are desirable for green carbon science.

**NSR:** Despite substantial progress in the preparation of hierarchically porous materials, it could be argued that hierarchical porous structure cannot easily be designed and synthesized for a specific application. Do you have any suggestions or perspectives on the design theory for hierarchically porous materials?

**He:** At present, we still follow the process of trial, testing, modification and retesting to reach optimized, but not the best, target materials. This situation is because of the lack of principles, rules and theories on the design of advanced materials. ‘Material properties by design’ is an attractive concept for future development. Is it possible to establish material design principles to achieve predictive, optimized functions? I think that nature could yield important inspiration by providing concrete examples to help identify rules to follow and emulate. Many classes of organisms have hierarchically porous networks with extremely high efficiency and minimum energy consumption, such as plant stems, leaf veins, and vascular and respiratory systems. These living hierarchically porous networks connected within a finite volume can minimize the transport resistance to all the pores and ensure fluent transfer throughout the entire hierarchical network as a precondition for organisms.

Using the generalized Murray’s law, Prof. Bao-Lian Su’s group recently fabricated the first family of bioinspired materials emulating natural vascular structure. The pore sizes decreased across multiple scales and finally terminated in a size-invariant unit resembling the hierarchical structure of plant stems, leaf veins, and vascular and respiratory systems. These biomimics possessed hierarchical branching and strongly promoted mass exchange and transfer in liquid–solid, gas–solid and electrochemical reactions. This is the first example of quantitative materials design and synthesis of diameter ratios to connect multiscale pores from macro to micro levels. This work is a pioneering demonstration of the synthesis of simultaneously optimized multi-length-scale materials following design rules that evolved in natural hierarchical systems and that enable the functionality of material networks to be predictably controlled.

It is highly desirable to use this approach to construct other hierarchical networks of interconnected pores within materials. I am pleased to see that many industrial efforts have been devoted to this field; for example, the Shanghai Institute of Petrochemical Technology (Sinopec), led by Professor Zai-Ku Xie and Professor Wei-Min Yang, has put considerable effort into this field from the aspect of industrial applications. The concept of hierarchical materials has also been applied to metal-organic frameworks and fibers. I hope that this special topic of *National Science Review* focusing on hierarchically structured porous materials will attract much new research attention to boost progress in this field from laboratory to industry.

**NSR:** What suggestions would you make to young researchers entering the field of hierarchically porous materials?

**He:** Hierarchically porous materials have been extensively studied for many years and numerous achievements have been made. Young researchers should think carefully about what they can do before entering this field. I advise that they choose emerging or unsolved challenges as their focus based on their background and interests. They will need to combine other concepts such as confinement, shape selectivity and molecular recognition with hierarchically structured porous materials. New ideas come from the interface between scientific knowledge and unanswered questions. New discoveries and concepts quite often reside in the experimental facts that do not conform to expectations. Young researchers should always keep their curiosity and investigate what they are really interested in.

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—Ming-Yuan He"

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