# *IB* IN DEPTH–Cellulose Nanotechnology: Fundamentals and Applications

GUEST EDITORS: JOSE MORAN-MIRABAL AND EMILY CRANSTON

# Overview

## Cellulose Nanotechnology on the Rise

*Jose M. Moran-Mirabal and Emily D. Cranston*

*McMaster University, Hamilton, Canada*

The term ''nanotechnology'' evokes in our minds a wide range of images, from ultra-small particles and structures to smart materials and even, in the imagination of science fiction writers, an army of tiny robots that can be controlled at will. In practice, nanotechnology as a field of research and development entails the synthesis, study, or application of materials whose sizes are in the 0.1–100 nm scale or whose unique properties derive from a critical nanoscale dimension. The great promise of nanotechnology stems from the notion that using nanostructured matter could result in materials, technologies, or devices with enhanced properties that allow us to meet human needs in a more efficient and environmentally-friendly way.[1] In addition, the increasing demand for products made from sustainable, renewable, biocompatible, and non-petroleum-based materials has pushed nanotechnologists to look towards nature as a source for the next generation of nanomaterials.

Cellulose represents $\sim 1.5 \times 10^{12}$ tons of the total biomass produced yearly, and as such is the most abundant structural polymer in nature.[2] Cellulose has been used for millennia as a source of fuel, building materials, paper products, and textile fibers. Its widespread use is primarily due to the unique intrinsic physical, chemical, and mechanical properties that largely arise from the hierarchical organization of natural cellulosic materials. For example, the tight packing of glucan chains contained in the core of cellulose microfibrils gives plant cell walls the rigidity to withstand the mechanical stresses of their environment. Thus, even before cellulose was properly described by Payen in 1838, and before the first cellulose nanocrystals or nanofibrils were isolated from plants, the superior properties from the nanoscale dimensions of microfibrils were already being broadly employed.[3–5]

### Current Status

Nowadays, the arsenal of cellulosic nanomaterials at our disposal spans particles with lengths of tens of nanometers to millimeters and aspect ratios from 1 to 1000, as exemplified by the perspective and original research pieces included in this special issue of *Industrial Biotechnology*. What is more, we are learning that these nanocellulose materials not only exhibit the expected enhanced optical and mechanical properties, but also show unique piezoelectric, electric, and magnetic properties that either do not exist or cannot be exploited in their macroscale counterparts. The attributes of these materials and their great versatility have made nanotechnologists dub cellulosic nanomaterials in general, and cellulose nanocrystals and nanofibrils in particular, as ''nature's carbon nanotubes.''

Our ability to use cellulosic nanomaterials effectively in any intended application relies on our understanding of how these particles and fibers behave and how their unique properties change with particle dimensions (which are dictated by the various synthesis and isolation methods available). Thus, much research has focused on characterizing the physicochemical and material properties of cellulosic nanomaterials. These efforts have not only elucidated cellulose materials themselves, but have also paved the way for a deeper understanding of polymers in general and of carbohydrate chemistry in particular, especially in the areas of chemical functionalization and polymeric liquid crystals. Today, more than ever, we have at our disposal a multitude of sophisticated characterization techniques and tools that allow us to visualize cellulosic nanomaterials at their most elementary level, test long-standing hypotheses, and ultimately see an ''old'' material in a ''new light.'' Additionally, the knowledge gained from research on cellulosic nanomaterials can also be employed in a retroactive fashion to study cellulose in its natural settings and during biosynthesis, e.g., in plants, tunicates, algae, and bacteria, to elucidate the design rules that have made cellulose a core component of nature.

The study of cellulosic nanomaterials remains a very active area of highly interdisciplinary and collaborative research that transcends international borders, with strong efforts under way in the US, Canada, Japan, France, and Scandinavia, to name a few. As a result, what we have learned from studies that started as academic curiosities is now being translated into a number of commercial explorations. We have already seen the appearance


DOI: 10.1089/ind.2015.1501

of the first pilot- and industrial-scale producers of cellulose nanofibrils (e.g., Innventia, Borregard, Oji Paper, VTT, Daicel) and cellulose nanocrystals (e.g., CelluForce, Melodia, USDA Forest Products Lab, Alberta Innovates-Technology Futures).

The estimated global production of cellulosic nanomaterials is currently at ~340 tons per year and is conservatively forecasted to rise to 2,600 tons per year by 2020.[6] The current distribution of the nanomaterials produced by type is approximately 65% cellulose nanofibrils, 34% cellulose nanocrystals, and 1% bacterial cellulose; however, this landscape does not reflect the ease with which these materials are produced and is likely to shift due to the scale at which cellulose nanocrystals can be produced and their numerous applications.[6] These numbers highlight a surge in the research and translational development underway in the cellulosic nanomaterials area and it is noteworthy that considerable efforts in standardization (by ISO, TAPPI, and the Canadian Standards Association) are also in progress.

## Challenges

Despite the advances in cellulose nanotechnology, a number of interesting and important challenges remain. Perhaps the most obvious starting place when developing a commercial product is to pick the right nanomaterial for the right application, as each type of nanocellulose presents unique properties that make it appropriate for specific applications. In this regard, ongoing studies in laboratories around the world are adding to the available characterization data and know-how related to nanoparticle dispersion, optimizing material compatibility, surface functionalization, and tailoring of rheological, mechanical, and electromagnetic properties. This information is in high demand and will lead to more successful incorporation of nanocellulose into industrially relevant materials; a few examples are presented in this issue.

Other challenges to achieving successful commercialization of products based on cellulosic nanomaterials pertain to reproducibility in manufacturing, sustainability, and environmental and safety concerns. Thanks to extensive efforts by manufacturers and collaborations between industry and academia, great strides have also been achieved in these areas. Although overcoming the challenges facing cellulose nanotechnology might seem like a tall task, the science is rich and the investment is well justified based on the materials' potential. While the envisioned applications are vast and too numerous to list, some examples sought after currently by researchers and various industrial sectors alike include structural composites, cosmetics, foams, adhesives, food modifiers, and pharmaceuticals. Given the current focus on green technology and renewable and biodegradable materials, cellulose nanotechnology is a prosperous and rapidly growing area that we believe will continue to foster excitement and gain in importance over the coming years.

Jose M. Moran-Mirabal, PhD, is Assistant Professor, Department of Chemistry and Chemical Biology, McMaster University, 233 Arthur Bourns Building, 1280 Main St. West, Hamilton, ON, Canada L8S 4M1. Phone: 905-525-9140, ext. 24507; Fax: 905-522-2509; Email: moran-mirabal@mcmaster.ca

Emily D. Cranston, PhD, is Assistant Professor, Chemical Engineering, McMaster University, JHE-A412, Hamilton, ON, Canada L8S 4L7. Phone: 905-525-9140, ext. 24369; Email: ecranst@mcmaster.ca

REFERENCES

1. Hubbe MA, Rojas OJ, Lucia LA, Sain M. Cellulose nanocomposites: A review. *BioResources* 2008;3:929–980.
2. Klemm D, Heublein B, Fink HP. Cellulose: Fascinating biopolymer and sustainable raw material. *Angewandte Chemie* 2005;44:3358–3393.
3. Payen A. Mémoire sur la composition du tissu propre des plantes et du ligneux. *C R Hebd Seances Acad Sci* 1838;7:1052–1056.
4. Rånby BG, Banderet A, Sillén LG. Aqueous colloidal solutions of cellulose micelles. *Acta Chemica Scandinavica* 1949;3:649–650.
5. Turbak AF, Snyder FW, Sandberg KR. Microfibrillated cellulose, a new cellulose product: Properties, uses, and commercial potential. J Appl Polym Sci. 1983;37:815–827.
6. The Global Market for Nanocellulose to 2020. Future Markets Inc., 2013. Available at: www.futuremarketsinc.com/the-global-market-for-nanocellulose-to-2020/ (Last accessed April 2014).