Cellulose (2006) 13:115–118
DOI 10.1007/s10570-006-9056-1


# Advancing cellulose-based nanotechnology

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*Key words:* Cellulose, Forest products, Lignocellulose, Nanotechnology, Research, Wood

**Abstract**

Nanotechnology has applications across most economic sectors and allows the development of new enabling science with broad commercial potential. Cellulose and lignocellulose have great potential as nanomaterials because they are abundant, renewable, have a nanofibrillar structure, can be made multifunctional, and self-assemble into well-defined architectures. To exploit their potential, R&D investments must be made in the science and engineering that will fully determine the properties and characteristics of cellulose and lignocellulose at the nanoscale, develop the technologies to manipulate self-assembly and multifunctionallity, and develop these new technologies to the point where industry can produce advanced and cost-competitive cellulose and lignocellulose-based products. Because many of the findings on nanostructues and nanoprocesses are not yet fully measurable, replicable, or understood, it will take substantial R&D investments. To most effectively and efficiently move forward, increased cooperation must occur among the cellulose/lignocellulose R&D community, the federal departments and agencies having interests and ongoing programs in nanotechnology, and industry. Cooperation is critical to capturing synergies, enhancing accomplishments, and avoiding unwarranted duplication of facilities and efforts.

Technology is the major driving factor for growth at every level of an economy. Currently, most major Governments around the world are investing heavily in Nanotechnology and many see it as fueling the next Industrial Revolution. At the 1 nanometer (nm) scale and below, quantum mechanics rules, and at dimensions above 100 nm classical continuum mechanics, physics, and chemistry dictate properties of matter. Between 1 and 100 nm, a hybrid exists, and interesting things can happen. Mechanical, optical, electrical, magnetic, and a variety of other properties can behave quite differently, providing the opportunity to develop materials with higher strength, greater opacity, and enhanced electrical and magnetic performances among many others. Nanotechnology seeks to develop materials and structures that exhibit novel and significantly improved physical, chemical, and tribological properties and functions due to their nanoscale size; while Nanoscience seeks to understand these new properties. As defined, Nanotechnology involves the manipulation of materials measuring 100 nm or less in at least one dimension. Recent developments in analytical techniques such as Atomic Force Microscopy have helped us understand the structures of materials in much greater detail. In addition to size, these nanomaterials must display unique and novel properties and characteristics that are different than the bulk material properties. Nanotechnology will fundamentally change the way materials and devices are produced. The ability to liberate and obtain nanoscale building blocks with precisely controlled size and composition and assemble them into larger structures with unique properties and functions will revolutionize segments of the materials manufacturing industry. Nanotechnology can bring many benefits – lighter, stronger,

and multifunctional materials; innovative devices based on new principles and architectures; and use of molecular/cluster manufacturing, which takes advantage of assembly at the nanoscale level for a given end use. New structures not previously observed in nature are achievable. Nanotechnology has applications across nearly all economic sectors and allows the development of new critical enabling science with broad commercial potential, such as nanostructured materials, nanoscale-based manufacturing processes, and nanoelectronics. It is expected that Nanotechnology will have the most significant impact soonest in traditional industries who will be able to leverage the large amount of fundamental research currently under way.

Cellulose would appear to have great potential as a nanomaterial. Cellulose is one of our most abundant biological raw materials, has a nanofibrillar structure, and self-assembles into well-defined architectures at multiple scales ranging from the nanoscale to the macroscale. Cellulose has the potential to be the source for renewable materials, which can be made multifunctional and self-assembling and could displace many non-renewable materials including metals and ceramics. However, to fully exploit cellulose nanotechnology, research and development (R&D) investments must be made in the science and engineering that will fully determine the properties and characteristics of cellulose at the nanoscale, develop the technologies to manipulate cellulose self-assembly and multifunctionality within plants, and develop these new cellulose technologies to the point where industry can produce much more advanced and cost-competitive cellulose-based products. Because many of the findings on nanostructures and nanoprocesses are not yet fully measurable, replicable, or understood, it will take substantial investments to develop corresponding technologies.

## The path forward

In a first step in the US toward the goal of applying nanotechnology to cellulosics from trees for the forest products industry, a workshop was convened in October, 2004. From this workshop came a document titled ''Nanotechnology for the Forest Products Industry-Vision and Technology Roadmap.'' This forest products industry roadmap is available for downloading on a number of websites, including http://www.nanotechforest.org. This roadmap includes suggestions on developing a significant R&D effort. Specifically it advocates: (1) creating a partnership among government, industry, and universities to gain consensus on what the R&D focus should be for the short term, mid term, and long term and establishing a steering group that includes key stakeholder groups and key funding groups – the steering group would serve as a focal point and champion for the overall national R&D roadmap and aid in accelerating nanotechnology into the forest products industry; (2) linking the cellulose/lignocellulose research communities with the existing nanotechnology research community and the US National Nanotechnology Initiative and its participants such as the National Science Foundation (NSF), Department of Energy (DoE), and National Institute for Science and Technology (NIST); and (3) proposes that an R&D investment of $40–60 million dollars per year for forest products in the US be made by the Federal Government.

The next steps in achieving consensus on nanotechnology focus areas are accomplished by engaging key stakeholders in assessing market potentials, determining technological barriers and the feasibility of overcoming them, identifying assets and resources available, and identifying champions for the various program activities, defining funding needs, and identifying risk factors. Specific actions include – (1) developing a portfolio of R&D projects that are commensurate with the size and importance of the forest products industry; (2) identifying specific avenues of promising research and grouping these according to their development time horizons; (3) selecting applications that would be positively impacted by successful research and prioritizing them in terms of future potential to include the short term, mid term, and long term (high risk/high payoff); (4) identifying precompetitive technological needs for new enabling technologies and to set and focus research targets; (5) communicating industry priorities in nanotechnology R&D broadly to the university, federal laboratory, non-profit research communities; (6) linking with the already established nanotechnology research centers and research communities; and (7) developing effective funding strategies to support collaborative multi-

disciplinary research activities, demonstration, and validation of technology, along with the development of a workforce skilled in nanotechnology for the forest products industry.

## The national nanotechnology initiative

The US National Nanotechnology Initiative (NNI) was established in 2001 to coordinate the R&D of nanoscale science, engineering, and technology across the Federal Government. The Nanoscale Science, Engineering and Technology Subcommittee (NSET) coordinates the NNI and operates under the oversight of the National Science and Technology Council. In 2005, 11 agencies are investing a total of almost $1 billion for R&D. The vision of the NNI is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry. The four goals of NNI are to: (1) maintain a world-class R&D program aimed at realizing the full potential of nanotechnology; (2) facilitate transfer of new technologies into products for economic growth, jobs, and other public benefits; (3) support responsible development of nanotechnology; and (4) develop educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology. In addition, the NNI is advocating development of a national infrastructure that will provide access to user centers housing expensive and sophisticated equipment that is necessary but not cost effective for anyone group or institution to purchase and maintain. The NNI is also advocating the establishment of research centers with specific focuses and expertise that can be called upon as needed to solve narrow but complex problems. As a result, NSF has established over 16 university nanotechnology centers around the US, DoE is constructing five major user laboratories where researchers can gain access to very expensive but very necessary nanotechnology research equipment, and the National Institute of Health (NIH) among others are establishing programs and facilities that will help with environmental safety and health issues related to nanomaterials.

Increased cooperation must occur between the cellulose/lignocellulose R&D communities, the federal departments and agencies having ongoing programs in nanotechnology research and development, and the NNI. Linkages between cellulose/lignocellulose R&D communities and the NNI umbrella centers and user facilities (such as those sponsored by NSF, DoE, NIST, and NIH) are critical to capturing synergies, enhancing accomplishments, and avoiding needless duplication of facilities and other resources.

## Government–industry–university cooperation

Advancing a cellulose/lignocellulose nanotechnology R&D agenda in partnership requires gaining consensus on research needs and priorities among the forest products industry, universities with cellulose/lignocellulose research and education departments and programs, technology developers and suppliers, research institutes and laboratories serving the forest products industry, and mission-oriented federal agencies with supportive goals, such as NSF, U.S. Department of Agriculture (USDA), and DoE. In building consensus, the forest products sector can capitalize on the generally good working relationships that the forest products industry has with its university research community, and with federal agencies such as USDA Forest Service; USDA Cooperative Research, Education and Extension Service; DoE Industries of the Future Program; and the DoE Biomass Program. In addition, the US forest products sector can take advantage of the linkages it has with research communities internationally. In creating this partnership, the forest products industry can build upon already established and successful programs such as the American Forest and Paper Association's (AF&PA) Agenda 2020 Research Alliance. The Agenda 2020 Research Alliance is an industry led partnership with government and academia for collaborative, pre-competitive research, development and deployment. It has developed an industry-wide research agenda for the entire forest products industry to include paper, composites, and solid sawn lumber. Specifically, the Alliance has identified six major technological needs areas – advancing the forest biorefinery; positively impacting the environment; developing the next generation fiber recovery and utilization; creating breakthrough manufacturing technologies, advancing the wood products revolution; positively impacting the environment, and developing a technologically advanced workforce.

Through this Alliance, R&D efforts can be focused on high-impact, high-priority areas that will be the most critical to commercial production of nanomaterials and nanoproducts.

**Actions taken to date**

In 2005, the USDA Forest Service has become a member in and participates on the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Committee that oversees the NNI. Only federal departments and agencies can participate on this committee. NSET meets monthly to coordinate and report on activities and accomplishments of interest to the broader nanotechnology research community.

AF&PA Agenda 2020 Research Alliance has adopted nanotechnology as its seventh focus area and views nanotechnology as an enabling technology that can help overcome technological barriers in its six other needs areas. The Alliance is cross-cutting technological needs in the six areas with the nanotechnology roadmap and will be setting priorities from a commercialization point of view.

An *ad hoc* industry, university, federal agency steering committee has been formed in 2005 to champion nanotechnology, communicate R&D priorities, dialogue and link with the existing nanotechnology research communities, organize workshop and conferences on nanotechnology of interest to the forest products sector, and help raise the visibility of nanotechnology in the forest products community, the nanotechnology community, and the international forest products community.

The forest products university community through the Society of Wood Science and Technology (University of Tennessee) and the Pulp and Paper Education and Research Alliance (Georgia Institute of Technology and Auburn University) have teamed up to organize a NSF Workshop (September, 2005) directed at evaluating the research needs, opportunities, and benefits of separating, synthesizing, and engineering nanostructures from wood biopolymers into advanced materials and provide an opportunity by which national and international experts and other interested parties in nanotechnology science and engineering and forest products can exchange ideas and concepts. This is a first step in defining the fundamental science needs that would be of interest to NSF for its programs.

Planning has begun for two technical conferences on nanotechnology. The first is a symposium sponsored by the American Chemical Society Cellulose, Paper and Textiles Division to be held in March, 2006. The second is titled, the 1st International Conference on Nanotechnology for the Forest Products Industry. The international conference will be held in mid 2006 and will be organized by the Technical Association of the Pulp and Paper Industry.

Lastly, USDA CSREES and USDA Forest Service have efforts underway to define nanotechnology program objectives that fit the respective mission and goals of these agencies.

By undertaking the preceding and other related activities to raise the visibility of cellulose/lignocellulose as a major material in nanotechnology both nationally and internationally, it is expected that we can make the case for increased R&D investments.