The U.S. Forest Products Industry and Nanotechnology—the Green Connection

The U.S. forest products industry (through the American Forest & Paper Association Agenda 2020 Technology Alliance, Washington DC) has formed a formal working relationship and common technology agenda with the NNI-NSET (through the NNI-NSET-NILI Task Group). The forest products industry looks to nanotechnology as a means to tap the enormous undeveloped potential of trees as photochemical "factories" that produce abundant sources of raw materials using sunlight and water. Forest biomass resources provide a key platform for sustainable production of renewable, recyclable, and environmentally-preferable materials to meet the needs of society and reinvent the forest products industry in the twenty first century. Wood-based lignocellulosic materials from our Nation's commercial forests provide a vast material resource and are geographically dispersed.

The forest products nanotechnology roadmap (www.agenda2020.org) identifies the industry vision as "sustainably meeting the needs of present and future generations for wood-based materials and products by applying nanotechnology science and engineering to efficiently and effectively capture the entire range of values that wood-based lignocellulosic materials are capable of providing." The forest products industry sees its inherent strengths to include stewardship of an abundant, renewable, and sustainable raw material base; a manufacturing infrastructure that can process wood resources into a wide variety of consumer products; and being uniquely positioned to move into new growth markets centered on bio-based environmentally preferable products. The industry vision is well aligned with society's need for establishing a source of sustainable materials and products. Working together with industry, NSET members--including the USDA Forest Service, NIST and DOE, the following mutually supportable priority areas for nanotechnology in the forest product industry have been set.

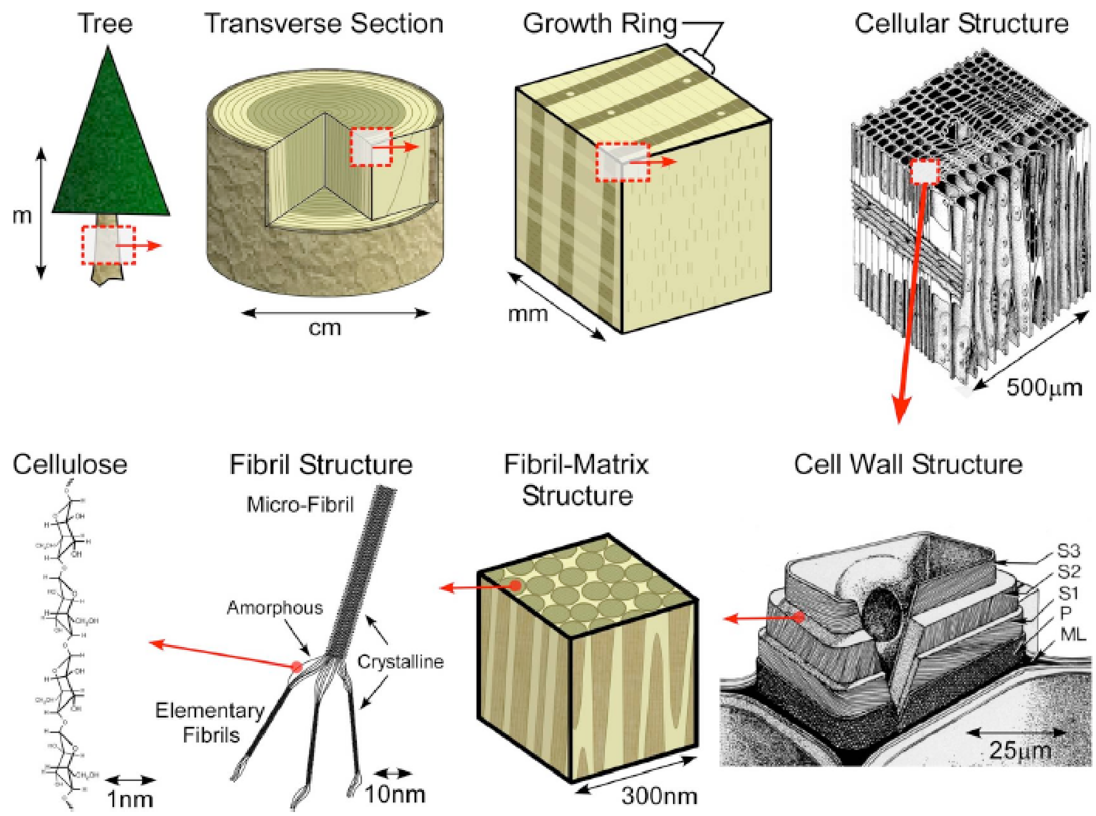
<u>Improving the Strength to Weight Performance.</u> The strength of lignocellulose-based fiber networks in paper and board products are controlled by matrix components, bonding strength, fiber strength, fiber size and shape, effects of any additives or fillers, and uniformity of material distribution. In addition, there are end-use product requirements for other key properties such as optical performance, surface smoothness, and stiffness. Large increases in strength-to-weight performance are not attainable with current technology and require breakthroughs in key areas: fiber network strength, optical properties, and surface enhancements.

<u>Liberation and use of nanocellulose and nanofibrils.</u> At the nanoscale, wood is composed of elementary nanofibrils (whiskers) which have cross-section dimensions of about 3–5 nm and are composed of cellulose polymer chains arranged in ordered (crystalline) and less ordered (amorphous) regions. Nanocrystalline cellulose has strength properties approximately equivalent to Kevlar® and the forest products industry focus is on liberation and use of both nanofibrils (amorphous and crystalline cellulose) and nanocrystalline cellulose. Success will allow the forest product industry to be a major supplier of nanoparticles for a wide-range of other industries. Because of the hundreds of millions of tons of wood available for processing, commercial production would be both sustainable and renewable as well as create an industrially significant supply. High value, renewable nano-enabled composites can be produced by identifying commercially attractive methods to liberate both nanofibrils and nanocrystalline cellulose and by establishing methods for characterization, stabilization, and blending of these wood-based nanomaterials with a variety of other nanomaterials.

<u>Understanding water-lignocellulosic interactions.</u> The response of wood and wood-based materials to moisture and their durability under high moisture conditions is due almost entirely to the super molecular structure of constituent biopolymers (i.e., cellulose, hemicelluloses and lignin) and nanoscale structures. An understanding of the interactions among moisture and woody material components at the nanoscale will enable development of new, innovative technologies that will improve both the durability and dimensional stability of wood and wood-based materials. In addition, understanding and manipulating the interactions between water and wood/paper should permit huge reductions in energy and water usage in converting wood to consumer products and allow more effective and efficient use of wood raw materials in a broad base of new and existing products.

High-performance nano-cellulosic enabled composites. Lignocellulose in woody plants is one of nature's most abundant materials and wood-based lignocellulose at the macroscale level is one of our most used and ubiquitous materials. To date, the intrinsic self-assembling nanoscale structure of lignocellulose, as well as the versatility of its constitutive biopolymers, has not been fully exploited. Cellulose is a material which has unique tensile properties. Potential composite properties besides strength include formability and geometrical complexity at the nanoscale, resulting in other unique physical properties, surface smoothness, biomedical compatibility, and ability to reinforce polymer foams.

Nano-photonics. Many grades of paper require using higher grammage (basis weights) than needed, not because of strength property end use requirements but because of the need to achieve sufficient opacity. More efficient optical performance with minimal weight will benefit all grade levels but especially the ultra-lightweight grades where opacity decreases rapidly with weight. Benefits include significant reduction in materials, processing and distribution costs. In order to be able to make high opacity coated paper in the same weight range of tissue paper, combinations with nanomaterials such as graphene, carbon nanotubes for electronics, optic manipulating nanomaterials, nanomaterials for high strength applications, and nanomaterials to control ink interaction must be explored.



Wood is a cellular hierarchical biocomposite made up of cellulose, hemicellulose, lignin, extractives and trace elements. At the nanoscale level, wood is a cellulosic fibrillar composite. Wood is approximately 30 – 40 percent cellulose by weight with about half of the cellulose in nanocrystalline form and half in amorphous form. Nanocrystalline cellulose is relatively uniform in diameter and length and these dimensions vary with plant species. Cellulose is the most common organic polymer in the World representing about 1.5 x 10^{12} tons of the total annual biomass production. Cellulose is expressed from enzyme rosettes as 3 - 5 nm diameter fibrils that aggregate into larger microfibrils up to 20 nm in diameter. These fibrils self assemble in a manner similar to liquid crystals leading to nanodimensional and larger structures seen in typical plant cell walls. The theoretical modulus of a cellulose molecule is around 250 GPa, but measurements for the stiffness of cellulose in the cell wall are around 130 GPa. This means that cellulose is a high performance material comparable with the best fibers technology can produce.