The Promise of Wood-Based NANOTECHNOLOGY

Finding new, high-value, market-based outlets for excess forest biomass is vital to forest restoration

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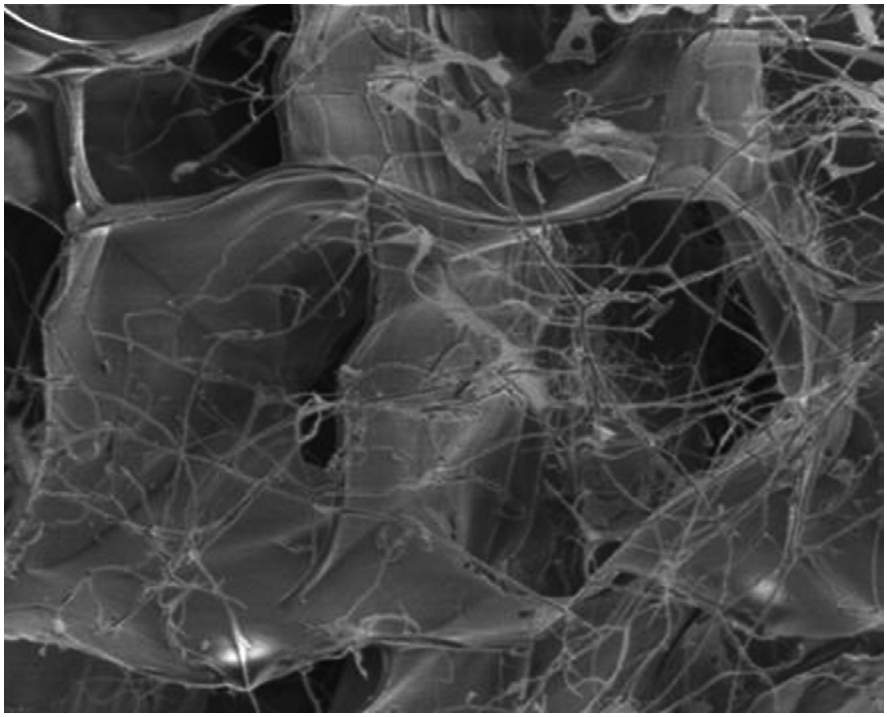

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Close-up of cellulose nanofibrils.

At first glance, wood-based nanotechnology and accelerated forest restoration may not seem connected. About 400 million acres of forest land across all ownerships in America need restoration. Typically, restoration means removing excess forest biomass. If there are no market outlets for this excess forest biomass it often accumulates until a catastrophic wildfire occurs. Finding new, high-value, market-based outlets for excess forest biomass is vital to accelerate forest restoration. This is where wood-based nanotechnology makes the connection.

Wood is made up of nanometer-size building blocks with properties that are orders of magnitude greater than the aggregate wood itself.[1] These nano building blocks do not require large-diameter trees, cost less than other nanomaterials to produce, and have much higher value than other forest products. Applications for these materials include coatings; lightweight, high-strength panels for construction; flexible electronic displays; parts for aerospace and automobiles; films; photovoltaics; polymer composites reinforcement; medical applications; sensors; and a host of other industrial tools and consumer products.[2]

ACCELERATING FOREST RESTORATION

Finding high-value, high-volume uses for low-value forest biomass (i.e., hazardous fuels) is one of the most important approaches to effective forest management.[3] The Forest Service approach to accelerating forest restoration is based, in part, on creating high-value markets for low-value wood.

Fighting wildfire is extremely costly, and the loss in lives and property is devastating. Fire suppression now accounts for over half the annual USDA Forest Service budget, and this continues to grow unabated. Forest restoration operations are also costly. For example, mechanical thinning costs the Forest Service about $1,000 per acre. Where wood utilization infrastructure exists, sale of the merchantable trees from mechanical thinning can recover some

of this cost, but full cost recovery is seldom possible.

In the late 1990s, the General Accounting Office (GAO) concluded that "the most extensive and serious problem related to the health of forests in the interior West is the over-accumulation of vegetation, which has caused an increasing number of large, intense, uncontrollable, and catastrophically destructive wildfires." This prompted a series of reports addressing hazardous fuels treatments. In developing the National Fire Plan in 2001, about $850 million annually was thought to be required. More recently, the GAO concluded that $69 billion would be required over a 16-year period—that's $4.3 billion per year. Relying on taxpayer dollars, the Forest Service has managed an average of only $300 million annually for hazardous fuels treatment.

Cost estimates for reducing hazardous fuels vary. What does not vary is the fact that fire suppression costs are increasing and the impacts are more severe. If we want a future without wildfires as destructive behemoths, we must create new large-scale markets for forest biomass. Cellulose nanomaterials derived through wood-based nanotechnology have the market potential and value to pay the full cost of forest restoration. A recent study estimated the market size for cellulose nanomaterials at 22 million tons per year, worth $100 billion annually and creating 300,000 new jobs. Commercial development of wood-based nanotechnology can accelerate forest restoration by as much as an estimated 12 million acres annually across all ownerships.

DEFINING WOOD-BASED NANOMATERIALS

Nanotechnology is defined as understanding and controlling matter at dimensions of approximately 1 to 100 nanometers.[4] Materials must also possess nanoscale properties that are uniquely different than their large-scale properties. In addition to very high strength and stiffness, nanomaterials derived from wood are piezoelectric[5] and have photonic[6] properties.

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Wood-derived cellulose nanomaterials come in two basic forms, cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs), with the highest quality and strength being produced exclusively from the cellulose component of wood. CNCs consist almost exclusively of nanodimensional cellulose crystals; CNFs consist of regions of crystalline and amorphous cellulose. Production methods include combinations of acid hydrolysis, enzymatic treatment, chemical treatment, and mechanical treatment. CNCs are uniform rods

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FPL's nanocellulose pilot plant is the first of its kind in the United States, situating FPL as the leading producer of domestic, renewable, forest-based nanomaterials. The plant can produce semicommercial-scale batches of cellulose nanofibrils and cellulose nanocrystals from renewable, wood-based sources.

Independent laboratories around the world have demonstrated that wood-derived nanomaterials will likely become viable commercial products. Continued work on applications is critical.

about 6 nm in diameter and 150-200 nm long. Dimensions of CNFs vary greatly depending on the method used to prepare them. The highest quality CNFs are produced using a combination of chemical and mechanical treatment, providing string-like filaments about 6 nm in diameter and 1,000 nm long. Lower quality CNFs can be produced by mechanically grinding wood pulp or even wood fiber. In these cases, various amounts of hemicellulose and lignin are part of the CNFs, and a range of nanodimensional sizes is produced.

APPLICATIONS FOR NANOMATERIALS

Potential product applications for wood-based cellulose nanomaterials are extensive. The largest volume commercial applications are in lightweight and high-strength composites. Production energy requirements and environmental footprint are generally lower than for competing materials including glass fiber, carbon fiber, and polymers derived from petroleum. For example, automotive applications are for lightweight parts to improve fuel efficiency and "green" sustainably sourced materials to reduce the environmental footprint. Weight reduction applications include high-strength cellulosic nanomaterials for composite exterior panels and structural parts.

Reinforcement of composite products. This market is very large, and nearly all products are higher value. Current fiber-reinforced products range from wood-fiber-filled plastic decking boards to carbon-fiber-reinforced

Chemical Engineer Richard Reiner (left) and Supervisory Research Chemist Alan Rudie (right) produce cellulose nano material in FPL's Nanocellulose Pilot Plant.

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Supervisory Research Chemist Dr. Alan W. Rudie (left) and Chemical Engineer Richard S. Reiner (right) stand behind their science, and a hefty batch of Cellulose NanoCrystals produced in FPL's state-of-the-art pilot plant.

structural aircraft parts. Cellulose nanomaterials can be substituted for other fiber reinforcement in all but the most demanding applications. Other high-end applications for cellulose nanomaterial reinforcement include lightweight armor and impact-resistant glass.

Films and coatings. CNFs produce clear films with high stiffness and good barrier properties. Addition of nano-sized clay impedes oxygen penetration, producing a film that can rival the barrier protection of aluminum foil. Use of CNCs and CNFs in paints and other coatings improves strength and greatly increases abrasion resistance. CNCs or CNFs used in coating paper and paperboard can be applied as a pre-coat to increase bending stiffness and coating holdout, or as part of the coating formulation to increase coating strength and smoothness.

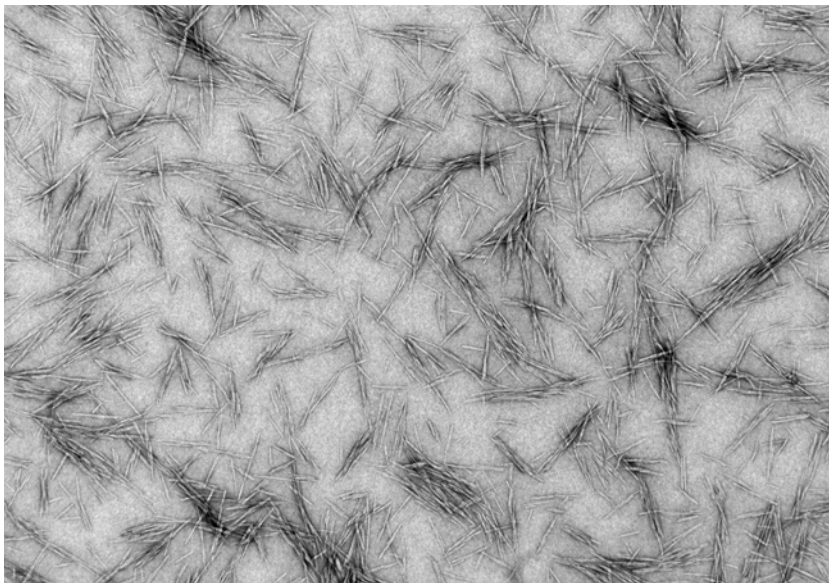
Electronics and photovoltaics. CNCs and CNFs can serve as substrates for photovoltaics and flexible and printed electronics and as insulating barrier layers in printed circuits, and they have been incorporated into battery electrodes and the charging layer of capacitors.

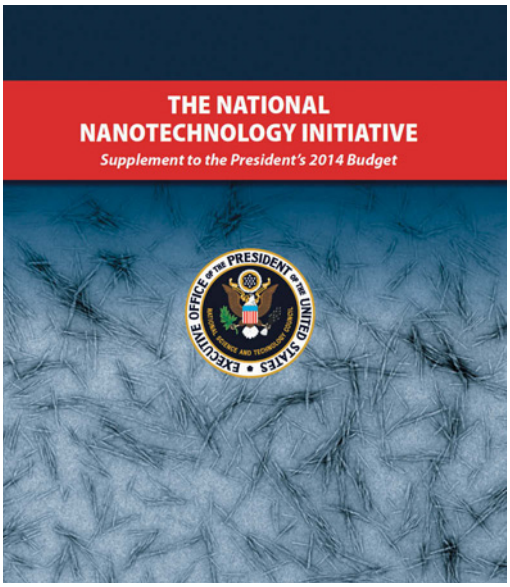
Medical. A bacterial form of CNFs has been used as a scaffold for skin grafts and several other applications for a decade. Wood- and cotton-based CNFs are being evaluated for similar applications. Synthetic tendons and cartilage produced from CNFs are hoped to temporarily replace damaged connective tissue while the body recruits cells to regrow supporting tissue, as it does with skin grafts.

Companies showing interest in these various applications of cellulose nanomaterials include DuPont, Ford, General Motors, Hewlett-Packard, Hyundai-Kia, IBM, Lockheed Martin, PepsiCo, and 3M.

FOREST PRODUCTS LABORATORY AND NANOCELLULOSE PRODUCTION

The Forest Products Laboratory (FPL) started a wood-based nanotechnology research program in 2006. In 2007, the Forest Service joined the National Nanotechnology Initiative (NNI), a collaboration of 26 federal agencies. It was





Transmission electron micrograph (TEM) of cellulose nanocrystals (CNCs) produced from commercial eucalyptus bleached kraft pulp by strong acid hydrolysis. The CNCs have relatively uniform physical dimensions (diameter of approximately 10 nanometers and length of 50 to 100 nanometers). Because CNCs have excellent physical strength but are lightweight (density of 1.5 grams per cubic centimeter) and optically clear, they can be used in applications such as electronics, reinforcing fillers for polymers, fibers and textiles, separation membranes, and biomedical implants. The CNCs were produced by researchers at the USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. The TEM of the CNCs was acquired by the Nanotechnology Characterization Laboratory of the Frederick National Laboratory for Cancer Research, funded by the National Cancer Institute. Cover design is by Kathy Tresnak of Koncept, Inc. Book design is by staff of the National Nanotechnology Coordination Office (NNCO).

soon recognized that research progress was being hindered by a lack of repeatable quantities of wood-derived CNCs and CNFs. In 2010, the Forest Service funded construction of a $1.7 million facility at the FPL to provide CNCs and the TEMPO-oxidized CNF variant.[7] The FPL facility produces 25-kg batches of CNCs and 2-kg batches of CNFs. In 2011, the Forest Service provided an additional $1.5 million for facilities at the University of Maine for other grades of CNF. CNCs are also produced at pilot scale by CelluForce (Canada, 1 ton/day) and Alberta Innovates (Canada, 20 kg/day). CNFs are produced at pilot scale in plants in Japan (Nippon Industries, 100 kg/day), Sweden (Innventia, 100 kg/day), UPM- Kymmene (Finland, 1 ton/day), and Stora Enso (Finland, 1 ton/day).

THE COMMERCIALIZATION PATH FORWARD

Independent laboratories around the world have demonstrated that wood-derived nanomaterials will likely become viable commercial products. Continued work on applications is critical—larger scale applications must be successfully demonstrated to provide incentive for large private sector investments. The largest volume uses will likely be for reinforcing composites, films, and coatings. In these higher volume uses, price is important. To move commercialization forward, the Forest Service works in formal and informal partnerships with a U.S.-based consortium of the paper industry, the National Nanotechnology Initiative, other Federal agencies/departments, and the U.S. Endowment for Forestry and Communities, and internationally with counterpart institutions in Canada and Finland.

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REFERENCES

1. One nanometer (nm) = 0.0000000393 inches—that's obviously a very small unit of length!
2. Michael T. Rains, Ted Wegner and Agenda 2020 Technology Alliance, September 24, 2012.
3. Shiloh Sundstrom, Max Nielsen-Pincus, Cassandra Moseley and Sarah McCaffery, "Woody Biomass Use Trends, Barriers, and Strategies: Perspectives of US Forest Service Mangers."Journal of Forestry, January/February 2012, pp. 16-24.
4. J. A. Shatkins and J. Cowie, Projections of Cellulose Nanomaterial Enabled Products. Vireo Advisors, 2013.
5. Piezoelectricity is a materials property where crystals placed under stress produce an electric field. This is the technology used to provide the spark in propane lighters.
6. Photonic effects are any material properties that affect light. In the case of cellulose, the primary one is circular polarization, which simultaneously selects for light that is polarized (like sunglasses) and of a specific wavelength or color.
7. TEMPO is the abbreviated name for 2,2,6,6-tetramethyl-1-piperidinyloxy. It selectively oxidizes a portion of the cellulose polymer chain to introduce enough negative charged groups to improve the separation of the wood fiber wall into individual cellulose fibrils. Think of a girl with long hair and her hand on a Van de Graf generator.