



NANOTECHNOLOGY AND THE FOREST PRODUCTS INDUSTRY: COMMERCIAL OPPORTUNITIES

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Nanotechnology and the Forest Products Industry: Commercial Opportunities

Executive Summary

In 2006, a Dovetail report, *Nanotechnology and the Forest Products Industry: Exciting New Possibilities*¹, explored the potential for development of new and improved wood products through nanotechnology. Nanotechnology is the *manipulation of molecular building blocks to create or modify materials*. Involving a scale of 1 to 100 nanometers (one inch is equivalent to over 25 million nanometers), nanotechnology offers exciting opportunities in a wide range of fields, including materials science and engineering.

Ten years ago, applications in nanotechnology with wood were focused on nano-manipulation of wood fibers to improve coating durability, moisture control, and extractive settling. Self-assembly was a major focus as well, which applies the natural growing patterns of cellulose to the development of products which self-assemble using little or no energy. In recent years, interests and opportunities for nanotechnology in the forest products industry have expanded to include diverse commercial applications in paper and packaging, food, health, the automotive sector, construction, sensors, and electronics. Expanded research investment can support the further commercialization of nanotechnologies. There are also some considerations of potential health and safety concerns that need to be better understood.

With roots in the 1950s, the technology of nanotech is not new, but current breakthroughs show incredible promise. Scientists and inventors are predicting that nanotechnology will be the next big thing, even defining our futures. One of these scientists is Dr. Ray Kurzweil, who is highly regarded for accurate predictions about future technologies. Dr. Kurzweil predicts that nanotechnology will be one of the three technologies to change our lives because it allows manipulation of matter at the molecular and atomic scale.² He notes that mankind will be able to create just about any physical object with very inexpensive input materials. Kurzweil also suggests that nanotechnology will be a billion times more powerful in just 25 years, creating almost unimaginable opportunities.³ This report picks up where our last report left off and explores the newest commercial opportunities for nanotechnology and the forest products industry.

Nanocellulose Production

Cellulose is the most abundant natural polymer available and is a significant structural component of plants. Cotton, for example is generally between 92-99% cellulose and wood contains between 45-50% cellulose by weight. Cellulose is biodegradable and renewable. The main sources of cellulose today are wood pulp and cotton, with industrial infrastructure in place for large-scale harvest and processing. However, cellulose is also commercially available from a wide variety of other plants, including sisal, jute, ramie and flax, as well as from algae and many agricultural “wastes.”

¹ Bowyer et al. (2006); available at: http://www.dovetailinc.org/report_pdfs/2006/dovetailnanotec0906.pdf

² McShane et al. (2016)

³ Kurzweil, R. (2016). Ray Kurzweil on the future of Nanotechnology. Available at: <http://bigthink.com/videos/ray-kurzweil-on-the-future-of-nanotechnology>

Wood fibers are formed from layered sheaths of cellulose microfibrils and these microfibrils are in part made up of elementary fibrils. Elementary fibrils are aggregates of individual cellulose molecules with diameters of 2-20 nm (nanometers). The use of wood in nanotechnology involves breaking down the wood fiber into its nanocellulose components, which are light, stiff, conductive, and transparent. Nanocellulose is also eight times stronger than steel in tension.⁴ Nanocellulose, in the form of nano-scale crystals, nanofibers or nanofibrils, has possible uses ranging from the paper industry to the electronics field.

In nanotechnology development, a great deal of attention is focused on carbon nanotubes, extremely high-strength structures created using graphite as a carbon source. Carbon nanotubes are rolls of single atom thickness sheets of carbon (graphene) which are conductive, strong, and flexible.

Carbon nanofibers are not as strong as carbon nanotubes. Carbon nanotubes are, in fact, as much as ten times stronger⁵ than nanocellulose and can be used for energy storage, automotive parts, electronics, and even in seemingly science fiction applications such as a ‘space elevator’⁶ and implantation in spider silk to produce Spider-Man-like webs.⁷ Given the much greater strength of carbon-based materials, one might wonder why there is interest in nanocellulose. The answer is that nanofibers are far less costly and less energy intensive to produce, and quite strong. Such fibers are cost-competitive because they are obtained from abundant biomaterial and are available from a variety of common sources, such as wood, bamboo, agricultural crop residues, and algae. Beyond environmental and cost benefits, more is known about the structure and synthesis of nanocellulose than of carbon nanotube formation. At this point, nanotube formation from carbon remains a mystery, leading to imperfect manufacturing. As a result of all of these factors, there is intense interest in nanocellulose, and a myriad of opportunities to improve the design and function of many products at low cost and with reduced energy consumption through its use.

In applications where carbon nanotubes are preferred, graphite is not the only potential raw material. Research at the University of Maine, and elsewhere, has revealed that plant fiber can also be used in carbon nanotube production, using the fiber of wood or other plants as the source of carbon. Consequently, whether interested in carbon nanotubes or carbon nanofibers, plant materials can be the starting point. This discovery positions wood and other renewable plant fiber as key materials in nanotechnology development.

⁴ Soutter (2012)

⁵ Yu et al. (2000)

⁶ Built with diamond-core nanothreads, see: <http://www.cnn.com/2014/10/10/tech/innovation/space-elevator-nanotechnology/index.html>

⁷ Steven et al. (2013)

Cellulose Nanocrystals (CNCs) and Cellulose Nanofibrils (CNFs)

Naturally occurring bulk cellulose consists of shapeless, amorphous regions as well as structured, crystalline areas that can be exploited by different processing methods. The two types of nanocellulose – cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs) – are prepared differently because they utilize these contrasting properties of wood cells. CNCs are nearly perfect crystalline particles with rice or rod-like shapes (Figure 1), while CNFs are random bundles of nanocellulose fibers that look more like spaghetti (Figure 2).

Figure 1. Cellulose nanocrystals

image from acceler8or

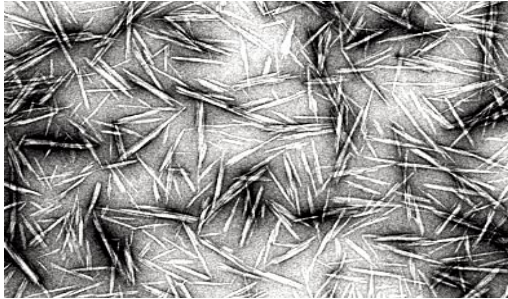
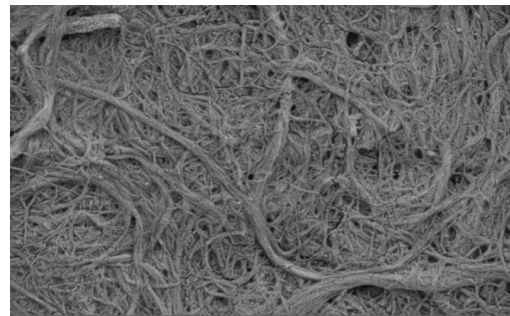


Figure 2. Cellulose nanofibrils

image from American Process Inc.



Many plant materials contain cellulose, but typically wood pulp is used as a starting point in nanocellulose production. Mixing a strong acid with wood pulp destroys the naturally formless parts and leaves crystalline nanoparticles, CNCs. Cellulose nanofibrils, on the other hand, are prepared by high shearing and homogenization of wood pulp at high pressure, which essentially grinds the cellulose into random bundles.

Paving the way for commercial development of nanocellulose in the U.S is the USDA Forest Services' Forest Products Lab (FPL) in Madison, Wisconsin, which built the first nanocellulose pilot plant in the U.S. in 2012. Scientists at FPL hope to spur the commercialization of nanocellulose in order to grow support for forest product markets. The University of Maine, with help from the USDA, has also built a facility with the capacity to produce a full ton of cellulose nanofibrils per day.⁸ The University of Maine Process Development Center (PDC) supplies cellulose nanomaterials, in the form of both cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF), to educational institutions, companies and public and private research groups interested in evaluating this cutting-edge material. The US Forest Service's Cellulose Nanomaterials Pilot Plant FPL is the source of the CNC, and the facility in Maine manufactures the CNF.⁹ The very first facility of this kind, Innventia, was built in Sweden in 2011 and produces 100 kilograms per day of nanofibrils for use in research and development activity.¹⁰

⁸ Wallace (2013)

⁹ <http://umaine.edu/pdc/cellulose-nano-crystals/>

¹⁰ O'Brien (2011)

Commercial Applications of Nanocellulose

Cellulose nanomaterials remain primarily in the research and development stage, but as illustrated in the following applications, commercialization may be on the horizon for a broad market. Potential applications include paper and packaging, food, health, automotive, construction, sensors, and electronics. Nanocellulose can enhance the properties of existing products and also introduce an environmentally friendly element because in many cases it appears possible to use natural wood fiber to replace harsher, more energy intensive substances.

Paper and Packaging

Nanocellulose in the paper industry is thought to have the greatest near-term market potential, wherein nanofibrils could be used as filler to improve strength-to-weight ratio, water resistance, and smoothness of specialty papers. Nanotechnology may also improve the recyclability of paper.¹¹ Nanocellulose can reduce the weight of paper by as much as 12.5 g/m²¹², while at the same time replacing clay or synthetic fillers; the potential weight reduction would be as much as 8-20%. Recently, American Process Inc. announced nanocellulose-enhanced, lightweight packaging, GreenBox++™, which is stronger than their previously chemically-pulped packaging and which reportedly has a lower carbon footprint.¹³ In the food packaging industry, nanocellulose can be used to create spoil-resistant packaging. A study in Canada, and published in the *Critical Reviews in Food Science and Nutrition*, showed that nanocellulose-based food packaging increases the shelf life of foods. For example sliced bread was found acceptable for 1 month and bacterial growth on meats and poultry was inhibited for 12 weeks in refrigerated conditions. In the future, sensors imbedded in the packaging itself could warn of spoiling or changes in moisture levels.

Food

Because cellulose is a natural plant material, it can be used in foods as filler and to reduce carbohydrates. Innventia did a study which showed that cellulose as an additive in hamburger resulted in burgers that generally taste and feel the same, but when fried are juicier as a result of holding more water. Many of the foods we eat already have cellulose fillers in them, usually products marketed as reduced fat or high fiber.¹⁴ The cellulose filler is not digested by our bodies, and it should be noted that cellulose also has no nutritional value. The cellulose additive is an alternative to added sugars and fats that is less costly for food producers.¹⁵

¹¹ The recycling benefits of nanotechnology are further described in Bowyer et al. (2006); available at: http://www.dovetailinc.org/report_pdfs/2006/dovetailnanotec0906.pdf

¹² Shatkin et al. (2014), Cowie et al. (2014)

¹³ Nelson (2016)

¹⁴ <http://www.wsj.com/articles/SB10001424052748703834804576300991196803916>

¹⁵ It is worth noting that some consumer advocates have raised concerns of false advertising when foods contain cellulose. For example, see: <http://www.bloomberg.com/news/articles/2016-02-16/the-parmesan-cheese-you-sprinkle-on-your-penne-could-be-wood>

Health

Health applications include wound dressings, tissue engineering and scaffolding¹⁶, and better medicine delivery mechanisms. Nanocellulose is ideal for these applications because it is nontoxic and has good thermodynamic properties. Research published in the *Journal of Applied Polymer Science* found that nanocellulose is a better option than other natural polymers used in the biomedical industry because it is more compatible with the human body. The study authors also pointed out that more research needs to be done before nanocellulose use can become commercially viable.

Another potential application of nanocellulose is in decontaminating water filters that could be used in processing of drinking water, as well as for cleaning up messes such as oil spills. The University of Wisconsin-Madison and the Forest Products Laboratory have developed organic, nanocellulose aerogels which are porous, flexible, and lightweight for the use of cleaning up spills.

Automotive

Replacing traditional polymer composites with nanocellulose composites in automobile parts could reduce the overall weight of vehicles or aircraft, thus giving better fuel economy. Weyerhaeuser Company and Ford Motor Company are working together to replace fiberglass with cellulose nanofibrils to reduce their carbon footprint. American Process Inc (mentioned earlier for their GreenBox++™ work) and Futuris Automotive have partnered with researchers to produce lighter, nanocellulose-enhanced car parts which can replace heavy steel equivalents. Additives in paint and coatings can also reduce scratching and ultraviolet light damage; this potential was demonstrated when the Finnish Centre for Nanocellulosic Technologies investigated nanocellulose as an additive in polyurethane paints and varnishes and found improved durability.

Construction

In the construction industry, nanocellulose enhanced coatings improve the strength-to-weight ratio and water-resistance of materials. Purdue University found that nanocellulose enhancement of concrete improves its strength by thirty percent, while boosting recyclability of the widely used product. TENCEL® from Lenzing AG is a cellulose fiber which is used in the construction industry because it adds strength and reduces cracking in concrete while using less water than other fibers. Transparent wood is being researched by universities and companies for its uses in construction and even solar cells.¹⁷ Replacing the lignin with acrylic or epoxy in wood pulp results in a glass-like material, which when used in construction allows more light into buildings. Addition of the acrylic does make the product less eco-friendly than pure wood, but it is still more biodegradable than plastic and more insulating than glass. This could be utilized for solar cells because the transparent wood traps light and would improve the efficiency of current solar cells.¹⁸

¹⁶ Tissue engineering is the use of a combination of cells, engineering and materials methods, and suitable biochemical and physicochemical factors to improve or replace biological tissues. Tissue engineering involves the use of a scaffold for the formation of new viable tissue. https://en.wikipedia.org/wiki/Tissue_engineering

¹⁷ <http://www.treehugger.com/solar-technology/future-solar-cells-could-be-made-wood-fibers.html>

¹⁸ Graham (2016)

Sensors

The large surface area and biocompatibility of cellulose nanocrystals make an ideal base for biosensors.¹⁹ Addition of biologically active molecules, such as proteins, could produce sensors with diverse uses. In the medical field, sensors of this kind injected into the bloodstream could detect nitric acid, which indicates inflammation and would be useful in patient recovery. As mentioned earlier, use of these sensors in food packaging could detect spoiling or other changes. Sensors in wood products could be used to detect high moisture content zones and potential for decay, providing opportunity for proactive intervention. Applications also reach into national safety and law enforcement, as nanocellulose crystal sensors can detect the presence of explosives, drugs, or other chemicals.

Electronics

Nanofibrils improve recyclability in electronics, which is crucial for devices with short lifespans, like cell phones and batteries. The Forest Products Lab developed a cellphone chip with a nanocellulose support layer, which is eco-friendly and non-toxic, unlike the gallium arsenide it replaces.²⁰ The same concept is helping to create light and flexible batteries which will reduce the impact of batteries in landfills. A prototype battery was recently created which charges faster and lasts longer than an iPhone battery and stores enough energy to power a Tesla vehicle or even a home.²¹

Wood Protection

Nanotechnology can also be used to produce better wood products. Using nano-metals and nano-delivery systems to modify coatings at the molecular level results in products that make wood more durable and resistant to moisture changes, decay, fire, UV light, pests, and fungi. Some of these enhanced products are already on the market. Specifically, a company in Australia has created a water resistant coating called Nanoseal® Wood, which is marketed as water repellent but a unique ability to bond to the wood surface also protects it from UV light and decay. Protection in the form of biocides can be improved by metal nanomaterials, which promote even distribution while being non-degradable, odorless, and long lasting. Limitations in this area are mostly cost related, because nano-metals and nano-delivery mechanisms are not as cheap as nanocellulose. Also in the category of wood protection, as noted earlier, biosensors can signal potential trouble related to zones of high moisture content.

¹⁹ Biosensors, also called biological sensors, are chemical sensing devices with biological and electronic components that detect and transmit a signal. <http://www.news-medical.net/health/What-are-Biosensors.aspx>

²⁰ California lists gallium arsenide as a carcinogen, and it is considered a known carcinogen in animals. <http://oehha.ca.gov/proposition-65/cmr/chemicals-listed-effective-august-1-2008-known-state-california-cause-cancer-or>

²¹ Buhr (2014)

Barriers to Commercialization

With roots in the 1950s the technology of nanotech is not new, but current breakthroughs show incredible promise. Successful scientists and inventors are predicting that nanotechnology will be the next big thing, even defining our futures. One of these scientists is Dr. Ray Kurzweil, who is highly regarded for accurate predictions about future technologies. Dr. Kurzweil predicts that nanotechnology will be one of the three technologies to change our lives because it allows manipulation of matter at the molecular and atomic scale.²²

Despite great potential, commercialization of nanotechnology is proceeding slowly as fundamental research transitions to applications-oriented research and development. Health concerns present a potential barrier to rapid development, as early research suggests that working at the nano-scale could negatively impact human health. The Centers for Disease Control report that there is potential in a manufacturing environment for workers to be exposed to low-solubility nanoparticles that are more toxic than larger particles on a mass-for-mass basis, and that some nanoparticles can move from the respiratory system to other organs. Of the few studies which have been done on the new technology, one showed inflammation in the lungs of mice which had inhaled cellulose nanocrystals.²³ Another risk is that these technologies could be weaponized. Before nanocellulose and nanotechnology can be widely commercialized, the possible risks need to be further examined.

The Bottom Line

While the applications of nanocellulose seem as beneficial as they are plentiful, commercialization is only beginning to occur. Nanotechnology offers the opportunity to change the forest products industry, among others, because nanocellulose is less expensive than carbon-based nanotech, environmentally friendly, and may improve the recyclability and performance of countless products.

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Supporting Nanotech

In 2005, researchers and industry leaders gathered for a workshop, *Forest Products Industry-Vision and Technology Roadmap*. They developed a goal for the USDA to receive \$40-60 million in funding through the National Nanotechnology Initiative (NNI).^a The first time the USDA Forest Service reported research and development funding for nanotechnology was 2007 and by 2008 they were receiving \$7.6 million.^b In 2015, they received \$21.1 million of the NNI's total \$1.5 billion.^c

^a Society of American Foresters (2005)

^b NNI (2007)

^c NNI (2016)

²² McShane et al. (2016)

²³ Yanamala et al. (2014)

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