Market projections of cellulose nanomaterial-enabled products – Part 1: Applications

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ABSTRACT: Nanocellulose provides a new materials platform for the sustainable production of high-performance nano-enabled products in an array of applications. In this paper, potential applications for cellulose nanomaterials are identified as the first step toward estimating market volume. The overall study, presented in two parts, estimates market volume on the basis of estimated tonnage of cellulose nanomaterials rather than the dollar value of production or profits from production. In this paper, we first identified potential uses from literature, presentations, and patent reviews, and then categorized these under the broad headings of high-volume, low-volume, and emerging/novel applications. For each application, the rationale for using nanocellulose is explained. The companion paper, Part 2, explains the assumptions and calculation of application-specific market estimates. High- and low-volume consumption applications of cellulose nanomaterials were identified from published data as well as expert input. We categorized potential market sizes as high or low by considering applications where cellulose nanomaterials would replace existing materials and be used at a published or estimated rate for some fraction of an entire existing market. Novel applications for cellulose nanomaterials that are presently considered niche markets are also identified, but volumes were not estimated because of a lack of published supporting data. Annual U.S. market potential for identified applications of nanocellulose is estimated as 6.4 million metric tons, with a global market potential of 35 million metric tons. The greatest volume potential for use of cellulose nanomaterials is currently in paper and packaging applications. Other potentially high-volume uses are in the automotive, construction, personal care, and textile sectors.

Application: This study identifies the potential applications for nanoscale forms of cellulose and derives a methodology to estimate market volumes for its use in those applications. Applications are identified as high-volume, low-volume, and emerging sector applications. The methodology and estimates may be used for planning and research decision-making.

Nanotechnology has enormous promise to bring about fundamental changes and significant benefit to society, including to the forest products industry. The forest products industry is in a unique position to tap this huge potential in two primary ways. First, by becoming a user of nanotechnology materials and components in its products and processes, the industry can upgrade its processes and produce new high-performance consumer products from lignocellulosic-based materials safely and sustainably. Second, the industry is poised to become a producer and developer of novel, sustainable nanomaterials to replace higher impact materials such as those from fossil fuels. Use of nanoscale cellulose (nanocellulose) in composites will allow the production of much lighter weight materials by replacing metals and plastics, with widespread application to the forest products and other industries.

This study, presented in two parts, examines the potential size of the market for nanocellulosic materials that are anticipated to enter commercial production. The purpose is to create a baseline for a more detailed market studies on the products and markets that will ultimately be positively affected by cellulose nanomaterials. We do this by systematically evaluating potential markets and applications for nanocellulosic materials.

We used published data sources to ground-truth research demonstrating the utility of nanocellulosic material for a particular application. This paper describes the identification of markets and the potential uses for nanocellulose in each market. A companion paper [1] includes the methodology, assumptions, market estimates and an analysis of potential impacts on forested lands.

NANOTECHNOLOGY AND THE FOREST PRODUCTS SECTOR

Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications [2]. Work within the intersecting disciplines at the core of nanotechnology innovation—including physical, life, and social sciences and engineering—has revealed the potential of nanomaterials and nano-scale processes in both incremental and revolutionizing ways. In addition, nanotechnology has enabled development of entirely new materials and devices that can be applied to a variety of new and existing applications.

Although the progress of nanotechnology innovations to date has been significant, numerous challenges still exist, and the enormous potential anticipated from nano-scale research and development (R&D) is still far from realization. Exploitation of the full value of nanotechnology innovation depends on sustained fundamental R&D and on focused commercialization efforts. Barriers need to be lowered and pathways need to be streamlined to transfer emerging nanotechnologies into economically viable applications.

The U.S. Forest Service has a robust program of research and development in the use of cellulose-derived nanomaterials. With greater public and private investment, such as by the public/private partnership recently formed between the U.S. Department of Agriculture and the U.S. Endowment for Forestry and Communities (P3Nano), there is an immediate opportunity to build a world-leading program for the development and commercialization of nanotechnologies in the forest products industry. Applications of nanotechnology to the manufacture of forest-based products promise new value-added features, improved performance attributes, reduced energy intensity, and more efficient use of renewable and non-renewable materials. Liberation of nanocellulose and its use in composite materials will allow the production of much lighter weight materials to replace current composites in many applications. The manufacturers of packaging products, for example, are seeking ways to move away from plastics, glass, and metal packaging and substitute use of paper and paperboard, which offer sustainability benefits.

BENEFITS TO SOCIETY

Investments in nanotechnology for the forest products industry sector can have substantive and measurable beneficial effects for society in addition to those measured by increased Gross Domestic Product (GDP), increased employment, and creation of high paying, skilled jobs. These investments will usher in cost-effective and affordable production of sustainable materials and products close to the point where they are used, thus reducing transportation costs and energy required for transporting raw materials great distances, as is the practice now.

Renewable and sustainable materials enabled by nanotechnology have the potential to reduce materials and energy consumption because of unnecessary over-construction of products and structures, arising from our current lack of knowledge of nano-scale structures and interfaces. A nanotechnology-revitalized forest products industry can help enhance forest health and condition and help maintain land in forest by providing revenue so it can retard the current accelerating trends of forest fragmentation, parcelization, clearing, and conversion of forest lands to non-forest uses; increase recharge of water to aquifers as 90% of the precipitation that falls on a forest is retained; and provide the full array of other forest ecosystem services to include animal habitat, clean water, clean air, carbon sequestration, recreation, etc. Importantly, increased use of trees for commercial products may help facilitate forest health treatments that could reduce the cost and impacts of forest fires, a significant burden to the U.S. Forest Service.

The benefits of cellulose nanomaterials in products can include: increased tensile strength; decreased weight; improved barrier properties for sound, oxygen, and potentially moisture; optically transparent and/or color specific layer coatings; biodegradability; and renewability.

MARKET DRIVERS FOR SUSTAINABLE PRODUCTS

Increased concern about the environment and a consumer and market push for greater sustainability in the use of products and services are making the development and use of renewable materials and products one of the central priorities of this and coming decades. Resource constraints are driving a push toward bio-based products. Increased recognition of global climate change and its effects is behind a shift toward greater carbon neutrality associated with human economic endeavors, including manufacturing, transportation, and energy generation. Cellulose is the earth's most abundant organic substance, with an annual production in the biosphere of about 90 billion tons. The use of renewable forest material contributes to a lower carbon economy because trees absorb carbon dioxide and become sinks for carbon. Managed forests, one of the largest sustainably-managed biomass sources in the United States, have a high potential to reduce U.S. greenhouse gas emissions and foreign fossil fuel dependency by conversion of forest materials into novel materials and products such as nanomaterials, high-performance composites, chemicals, and transportation fuels [3].

The current demand for sustainability in products is driven by consumers and by retailers seeking to differentiate themselves by decreasing lifecycle impacts of products on the environment, reducing and minimizing packaging, and improving the sustainability of their supply chains [4]. Innovation toward more bio-based, environmentally friendly products is a growing trend, influencing business decisions and corporate investment globally [5]. The data indicate this trend is not a fad; safer and more sustainable product development is a growing segment [6]. As a renewable, low toxicity and biodegradable material that can displace petroleum-based packaging, metallic components, and other non-renewable materials, cellulose nanomaterials represent an important niche for more sustainable product design and development.

There are several drivers of sustainability in innovation. Consumers increasingly demand transparency in products, seeking to understand the types and sources of ingredients, as well as better packaging for them. Companies are increasingly required to report environmental performance to their customers and supply chain partners. The rapid increase in sustainability reporting also drives companies toward better performance on energy, water and material consumption, natural resource depletion, and impacts on climate as progress toward targeted goals is claimed.

The high cost of shipping goods to their destination is in part driven by fuel costs, so there is a trend toward lightweighting, or reducing the weight of packaging, to reduce energy and electricity costs of transporting goods. There is also a push to reduce energy, water and material consumption in product manufacturing, which lowers costs and increases profitability. Concerns about end-of-life product impacts also drive public and consumer interest in reusable, recoverable, compostable, and recyclable packaging to lower overall lifecycle impacts.

Consumers also demand safety from products, and the trend of "red-listing" substances over concerns about adverse health impacts is driving companies toward safer alternatives. Several plastic additives or precursors have been targeted over the years by governmental and non-governmental organizations over potential impacts. Regardless of whether third-party claims about toxicity are valid, the perception that they may be creates demand for ingredients with lower impacts.

Hundreds of standards have been developed for claiming or explaining the sustainable aspects of consumer products. The labeling and certification environment is diffuse with hundreds of standards used and differences in measurements and reporting, methodologies, and endpoints; the situation is confusing at best. Regardless, the public and large retailer demand for better product performance on the energy and environmental front is driving companies toward lower impact products.

APPLICATIONS

A combination of literature survey and interviews was used to identify potential applications for nanocellulose. Applications were identified that we estimated would have high or low volumes, as well as those that are novel and do not have current markets for comparison for the introduction of cellulose nanomaterials. The applications having the largest potential volume of cellulose nanomaterials are paper and paper packaging, textiles, cement, and automobile parts. Smaller volume applications include sensors, construction, aerospace materials, cosmetics, pharmaceuticals, and paint additives. Novel applications are innovations without current markets and may employ the electrical and photonic properties of cellulose nanomaterials. Additive manufacturing (3D printing) may become a very large volume user of cellulose nanomaterials for toys, architectural models, and parts, but more research is required before it can be ready for commercialization. **Table I** shows the identified applications and their categorization.

Some applications rely on the use of cellulose nanofibrils (CNF), produced by mechanical processes, whereas other applications employ cellulose nanocrystals (CNC). With respect to CNF-type cellulose nanomaterials, there are two main methods for producing them. One involves extensive chemical pre-treatment (TEMPO), while the other is performed almost through mechanical means with little chemical pre-treatment. Liberation of CNC generally requires chemical treatment to cleave the non-crystalline portions of cellulose fibers. Novel production methods are anticipated for both CNC and CNF

High Volume Applications	Low Volume Applications	Novel and Emerging Applications
Cement	Wallboard facing	Sensors – medical, environmental, industrial
Automotive body	Insulation	Reinforcement fiber – construction
Automotive interior	Aerospace structure	Water filtration
Packaging coatings	Aerospace interiors	Air filtration
Paper coatings	Aerogels for the oil and gas industry	Viscosity modifiers
Paper filler	Paint – architectural	Purification
Packaging filler	Paint – special purpose	Cosmetics
Replacement – plastic packaging	Paint – OEM applications	Excipients
Plastic film replacement		Organic LED
Hygiene and absorbent products		Flexible electronics
Textiles for clothing		Photovoltaics
		Recyclable electronics
		3D printing
		Photonic films

I. Identified applications of nanocellulose and their categorization.

that will improve efficiency, yield, and manufacturing costs, but TEMPO and mechanical means represent the main current production methods.

High volume applications

Automotive – body components

Because cellulose nanomaterials are inexpensive relative to other composite reinforcement fibers, it should be possible to use them in wide scale structural applications [7]. In fact, Ford has said that it will be able to create so many components out of such materials —from body panels to interior trim—that it could shave 340 kg off the weight of its cars [8]. Fuel efficiency standards create demand for lightweighting in vehicles. In the near term, the most likely adoption will be in applications already using composite materials, while steel replacement is an additional application. CNF can be used as stable, extremely reactive raw materials for technical applications while having the additional advantages over extraction-based products of being renewable, biologically produced, and biodegradable. Such applications include reinforcing (bio-) polymers to create very promising, environmentally safe, lightweight construction materials for the car industry.

Automotive – interiors

CNC has been incorporated in polyethylene (PE), polypropylene (PP), and biopolymers (PLA and PHA), where it enhances mechanical and barrier properties, as well as abrasion resistance. CNC is envisioned as improving prospects for using bio-plastics in interior automotive parts [9]. Further, the ability to create aerogels and structural foams can result in development of lightweight decorative and interior panels such as the dashboard and door panels.

Construction – cement; pre-stressed and pre-cast concrete (worldwide)

Concrete can be reinforced with a combination of cellulose nanomaterials and micro-cellulose fibrils to increase the toughness of an otherwise brittle material [10]. These fibers could provide the benefit of other micro- and nanofibril reinforcement systems at a fraction of the cost. The addition of up to 3% micro- and nanofibrils in combination increases the fracture energy by more than 50% relative to the unreinforced material, with little change in processing procedure. Benefits include reducing the volume of cement needed, which will lower material and labor costs and result in reduction in associated greenhouse gas emissions.

Packaging – fiber/plastic replacement

Cellulose nanomaterial-based foams are being studied for packaging applications in order to replace polystyrene-based foams [11]. The advantage of using cellulose nanomaterials instead of wood-based pulp fibers is that the CNF can reinforce the thin cells in the starch foam, replacing a polymer produced from fossil fuel with a renewable material that decreases weight.

Packaging – filler

There is demonstrated potential of cellulose nanomaterials applications to improve strength and weight properties in paperboard manufacture. Cellulose nanomaterials are expected to enhance the fiber-fiber bond strength and hence have a strong reinforcement effect on paper materials while using less cellulose pulp through the thickness [12]. The result will be lighter weight packaging, which reduces fuel cost and consumption associated with transportation.

Packaging – coating

Cellulose nanomaterials are anticipated to be useful as a barrier in grease-proof types of papers and as a wet-end additive to enhance retention of additives, as well as dry and wet strength, in commodity types of paper and board products [13]. Further, the addition of CNF to coatings improves ink adhesion to the surface, allowing papers to be thinner and lighter.

Packaging – film

The mechanical and optical properties of the cellulose nanomaterials make them an interesting material for reinforcing plastics. Cellulose nanomaterials have been reported to improve the performance of, for example, thermosetting resins, starch-based matrices, soy protein, rubber latex, and poly(lactide) [14]. The composite applications may be for use as coatings and films, paints, foams, and packaging. CNC can be aligned to produce tunable optical properties, including transparency color changes.

Paper – filler

Paper manufacturers want to increase the filler content in paper because clay is typically much less expensive than wood pulp. By adding fibrillated cellulose nanomaterials during the production process, wood pulp can be displaced and, because of the superior structural strength of cellulose nanomaterials, more filler can be added, cutting production costs [15]. In addition, it takes less energy to dry the paper because much less cellulose is needed through the thickness. The resulting paper has improved properties; it is less porous, the printing quality is higher, and it is less translucent. This application reduces material inputs and energy in the production stage, as well as supporting the lightweighting that improves energy efficiency in transportation.

Paper – coatings

A patent awarded to the European company UPM [16] says a 3 g/m^2 coating of CNF will permit less use of nano-clays, resulting in a reduction in weight of the paper by as much as 12.5 g/m^2 while maintaining the paper's strength. The University of Maine also uses 3 g/m^2 CNF in its research [17]. UPM is looking to use cellulose nanomaterials at the wet end of the paper machine to improve strength properties, as well as replacing synthetic binders in the paper coatings [18,19]. Adding CNF to coatings improves printing and lightweighting.

Personal care - hygiene and absorbent products

The super water absorbency of cellulose nanomaterials makes them an ideal biodegradable water retention filler in incontinence pads and diapers [20]. There is likely to be high demand for lighter, thinner and natural product alternatives in this market. The ability to compost rather than landfill or incinerate reduces impacts at the end-of-life.

Textiles – clothing

Cellulose has long been used to make textiles; rayon, for example, is made from pulp or cellulose. But recently, scientists have developed a highly processed form of cellulose nanomaterials [9]. Once mass produced, this will give engineers stronger, lighter, more durable textile materials to make clothing. The development of electrospinning techniques that produce continuous fibers can be applied to develop nanocellulose composite fabrics [21]. The movement toward more natural materials from textiles creates a consumer driver, while biodegradability decreases the end-of-life burden of textiles, which currently account for as much as 5% of municipal solid waste.

Low volume applications

Aerogels – oil and gas industry

A novel type of sponge-like material for the separation of mixed oil and water liquids has been prepared by the vapor deposition of hydrophobic silanes on ultra-porous cellulose nanomaterials aerogels. To achieve this, a highly porous (> 99%) cellulose nanomaterial aerogel with high structural flexibility and robustness is first formed by freeze-drying an aqueous dispersion of the cellulose nanomaterials. The hydrophobic lightweight aerogels are able to selectively absorb oil from water, with a capacity to absorb up to 45 times their own weight in oil. The oil can also be drained from the aerogel, and the aerogel can then be reused for a second absorption cycle [22,23].

Aerospace – structural

There is increasing attention on the performance advantages of nanocomposites, and polymer-based nanocomposites in particular, for weight-reducing initiatives. In the interest of sustainability, the specific use of bio-reinforced nanocomposite parts and nanostructured coatings within automotive, aerospace, construction, medical, and packaging applications is accelerating. These “green” nanocomposites can provide high mechanical strength at low density, low weight, and potentially low cost. New efforts are underway to develop and apply sustainable nanocomposites that improve structural properties for applications in the aerospace industry [15]. Typical properties that are improved over existing composites include dimensional stability, structural strength, thermal resistance, chemical resistance, weight reduction, and electrical conductivity. This application falls in the low-volume category because of the high performance requirements for new materials in aerospace, but over the longer term it will likely become a larger application with wide adoption.

Aerospace – interiors

Much like aero-structures, interiors are being designed with lighter weight materials. Beyond traditional applications in the floorboards, ceiling and panels, monuments and other components, seating has become a major focal point for composites applications [24]. Lightweighting of the seats can enable major aircraft weight reductions. Slimmer seat designs also allow operators to make some small increases in the number of seats per aircraft. The use of composites in seats and in a variety of small brackets, clips, trays, plinths, and other structures is increasing. Reducing weight on the aircraft increases fuel efficiency and reduces greenhouse gas emissions.

Construction – air and water filtration

Some researchers propose that aerogel particles could be used in filters to remove contaminants from both air and water. Cellulose is already used to filter out particulates in standard water treatment testing and to collect particles from the air. Water filters, for instance, often rely on activated carbon to absorb chemical impurities. This is just an absorptive charcoal filter with a slight positive electric charge to attract the negative ions in harmful chemicals. Such filters work very well, and experiments indicate that aerogels can absorb 130 times more pollutants than activated carbon [25]. Future aerogels may both prevent toxic spills, as well as help clean them up when a spill does occur. Nanocellulose can be made to selectively remove contaminants and is highly absorptive.

Construction – gypsum wallboard facing

Cellulose nanomaterials in wallboard facing makes drywall lighter, stronger, and water resistant, which ultimately makes it resistant to mold growth [26]. Lightweighting can reduce the lifecycle energy and material impacts of building materials, adding green building credits toward LEED certification, for example.

Construction – insulation and soundproofing

Over the past years, advancements have been made towards creating cheaper, thinner, more breathable insulating materials with higher R-values. There still is no perfect insulation, but aerogel is one of the top contenders [27]. This new material has the lowest bulk density of any known porous solid, as well as significant insulating qualities. This is in the low-volume category because while aerogel can make a highly insulating material with low energy inputs, it does not require much cellulose nanomaterial.

Industrial – viscosity modifiers

Cellulose nanomaterials are used as viscosity modifiers, gelling agents, foaming agents, and binding agents [28]. Currently, hydroxyethyl methyl cellulose is used in the production of cellulose films [29].

Industrial – water purification

Commercial companies are designing, developing and optimizing novel bio-based foams/filters/membranes/adsorbent materials with high and specific selectivity using combinations of cellulose nanomaterials/nano-chitin for decentralized industrial and domestic water treatment. A Swedish organization is developing a novel water purification approach combining the physical filtration process and the adsorption process exploring the capability of the cellulose nanomaterials and/or nano-chitin to selectively adsorb, store and desorb contaminants from industrial water and drinking water while passing through a highly porous or permeable membrane [30].

Paint

Nanocelluloses can modify the viscosity of paints and coatings. A Finnish group improved the durability of a coat of paint using cellulose nanomaterials as an additive in water-based polyurethane varnishes and paints [31]. According to this research, cellulose nanomaterials improve finish durability, and protect paints and varnishes from attrition caused by UV radiation. Extending the life of paints and coatings reduces the environmental burden of replacing coatings and the underlying material being protected.

Personal care – cosmetics

Cellulose nanomaterials may be used as a hydrating agent and non-allergenic rheology modifier, as well as for composite coating agents, in cosmetics (e.g., for hair, eyelashes, eyebrows, or nails) [32]. Demand for natural products, as well as high-performance colorants, increase the demand for these products.

Pharmaceuticals – excipients

Nanocellulose drug carriers may be produced in a bid to fight various types of illness-causing bacteria such as the ones that are resistant to antibiotics. The biocompatibility and biodegradability of nanocellulose is behind innovations to incorporate it into drugs and pharmaceutical delivery [33]. Powdered cellulose nanomaterials have also been suggested as an excipient in pharmaceutical compositions.

Sensors – medical, environmental, and industrial

CNC films are hygroscopic or water-absorbing, but individual crystals do not dissolve or even swell in water. For this reason, it is possible to use them in applications involving moisture (for example, humidity sensors) or for real-time contaminant detection. Cellulose nanomaterial-based sensors could help in monitoring structures like bridges to detect elevated stress. Modifying cellulose nanomaterials by double-walled carbon nanotubes and graphite carbon nano-powder expands applications for sensor applications [34]. The electrical conductance of these materials displays a high sensitivity to strain when tensile stress is applied.

Novel applications

Electronics – organic light emitting diodes (OLEDs)

Cellulose nanofibrils are being used in the development of next-generation flexible TV screen, computer screen, personal data assistant (PDA) screen, and other advertising display systems [35]. Optically transparent nano-composite films of bacterial cellulose and resin can be fabricated and used as a substrate for the OLED displays. The cellulose nanomaterials prepared from pulp fiber provide an excellent candidate for an OLED device substrate as well.

Successful depositions of transparent and conductive materials, including tin-doped indium oxide, carbon nanotubes and silver nano-wires, have been achieved on nano-paper substrates, opening up a wide range of applications in optoelectronics, such as displays, touch screens, and interactive paper [36]. The biodegradability of nanocellulose might aid in the recyclability of these devices to recover the valuable metallic components.

Photonic structures – films

Structural coloration is the production of color by microscopically structured surfaces fine enough to interfere with visible light, sometimes in combination with pigments: for example, peacock tail feathers are pigmented brown, but their structure makes them appear blue, turquoise, and green, and often they appear iridescent [37]. In plants, brilliant colors are produced by structures within cells. The most brilliant blue coloration known in any living tissue is found in the marble berries of *Pollia condensata*, where a spiral structure of cellulose fibers produces Bragg's law scattering of light. Interference is created by a range of photonic mechanisms, including diffraction gratings, selective mirrors, photonic crystals, crystal fibers, matrices of nano-channels, and proteins that can vary their configuration. Many of these mechanisms correspond to elaborate structures visible by electron microscopy. The application is the production of nano-enhanced films where reflected color is a function of the surface structure rather than a pigment [38].

Industrial and medical – additive manufacturing

Small, affordable 3D printers enable additive manufacturing of a single part. Architectural models and other professional demonstration items, particularly those that change often, create a variety of applications. Raw material for the 3D printers is usually various forms of plastic. Cellulose nanofibrils might be a perfect new sustainable and renewable raw material for 3D printers [39]. If nanocellulose can find its way into distributed additive manufacturing networks, countless objects, fabrics and products will be made from nanocellulose derived materials. Tissue scaffolding is one application currently being explored [40]. Consumer oriented applications, such as toys, jewelry and personalized gifts, are potential applications as well.

SUMMARY OF FINDINGS

Cellulose nanomaterials have the potential to improve the performance of many products and to displace non-renewable materials with cellulose—the earth's most abundant organic chemical. The products in which cellulose nanomaterials could be used range from traditional forest products (e.g., paper and packaging) to non-traditional (e.g., cement and precast concrete) to novel (e.g., flexible electronics). While some applications may be high-value specialty uses that consume relatively small amounts of cellulosic nanomaterials (e.g., pharmaceutical excipients), others could be higher-volume uses (e.g., auto body panels and interiors) that could have large impacts on the demand for wood fiber and, therefore, on the management of forested lands.

Based on current market size and the applications identified, the estimated U.S. volume of nanocellulose in the high volume category ranges from 3.6 to 9.3 million metric tons/year, with an average of 5.9 million metric tons/year. The low volume category is estimated to contribute an average of 0.48 million metric tons/year (range 0.23 to 0.7 million metric tons/year). Using simple GDP conversions, we estimate an average of 35 million metric tons/year on a global basis. We did not have a current market size as a basis for estimating volumes for applications in the novel category; however, these emerging areas may become significant segments of the market over time. In an accompanying paper [1], we provide the basis for the estimated potential market volumes for these applications, as initial estimates of market impact to guide more refined market analysis.

While CNC and CNF will likely face competing technologies in many potential applications, there will be some applications in which both the economics and the performance characteristics uniquely favor nanocellulose. The successful development of these markets will require continued public and private investment in the research and development, technology platforms, innovation, partnerships, and commercialization. **TJ**

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We chose to study this topic because the industry needs to know what the market potential is for nanocellulose, and also needs a rational approach to estimating that potential, which doesn't exist.

The available market studies for nanocellulose do not disclose how estimates were made, so we sought to provide a transparent methodology as a foundation for future work.

This research was challenging in that we made a number of assumptions about market adoption rates. We sought input from experts to ground truth these adoption rates.

It was surprising to discover the breadth of potential applications and possible volumes for nanocelluloses, and mill owners may want to look at how they can take advantage of this emerging nanocellulose market. Next, we will take a number of steps to refine the analysis and tailor it to the available types of nanocellulose.

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