Achieving Resource Sustainability and Enhancing Economic Development through Biomass Utilization

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1. INTRODUCTION

As the problems associated with sustaining and enhancing the world's forest and agricultural resources compete with the needs of a rapidly increasing and affluent population, the management of our land becomes a much more complex and important issue. One of the most important environmental features of wood and other woody-like fibers is that they are renewable and can be sustainably managed. Composite wood and natural biofiber products are beneficial to humans and to the environment in that they serve as environmentally effective alternatives to other non-renewable and/or non- or less-recyclable mineral- or petrochemical-based materials.

To enhance the development of engineered biocomposite products that meet the diverse needs of users and to maximize the sustainability of forest resources, research is needed that uses a materials science and engineering approach to improve biocomposite performance. We must commit ourselves to developing the fundamental and applied science and technology necessary to provide improved value, service-life, and utility while at the same time meeting the needs of our respective national and international consumers for sustainable building materials. We need to network with international collaborators to provide a broad range of tools to resource managers that, regardless for resource type or quality, promote sustainability and recyclability and reduce adverse environmental impacts. As a first step in addressing these issues and accomplish our mission, we have identified three (3) research needs.

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- Fundamental Biocomposite Science and Engineering
- Integrated Conversion Technology using Bio-refining, Bio-based products, and Bio-energy
- Nanotechnology

Each requires a progressively longer-term view and each has a progressively larger, but longer-range payback on the required research investment costs. As we begin to address these individual research needs and detail a few ways in which we can cooperate and collaborate to address these critical research needs, we need to discuss a few of the resource management, process engineering, and user expectations which hinder or currently prevent us from Achieving Resource Sustainability and Enhancing Economic Development through Biomass Utilization.

We must develop tools to address resource sustainability, enhance recyclability and minimize the environmental impacts of composite processing. Thus, as forest resource options change, as excess (e.g., discarded wood and fiber) waste-stream wood resources become available, as alternative non-wood and non-lignocellulosic materials become more economical and available, and as air and water quality regulations become more stringent, we must all work, each in our own way or together, to address each of these issues.

2. FUNDMENTAL BIOCOMPOSITE SCIENCE AND ENGINEERING

The world's timber supply is changing. Gone are the days of unlimited large-diameter temperate softwood and tropical hardwood timbers that produced wide lumber and large veneer logs. Further, changes in the industrial access to the government-controlled timber supplies, increased demand on smaller and more diverse timber resources, and an international need for assuring and enhancing forest resource sustainability highlight the critical opportunities that could be addressed by converting from a society based on using solid-sawn lumber/timber to a society based on using biocomposite materials. To a large extent today and to a far greater extent in the future, the main sources of wood and biofiber for engineered biocomposites will be (1) trees produced from unmanaged stands, (2) trees produced from managed stands, (3) trees produced under sustainable forestry principles and emerging practices, (4) plantation-grown trees, (5) recovered (i.e., recycled) wood, paper and paperboard, (6) wood residues from industrial/manufacturing operations, (7) agriculture fibers and crops, and (8) other woody-like biomass (i.e., bamboo and rattan) .

There are a host of woody and agro-fiber raw material sources for alternative composite products. Forest biomass on Federal forests in much of the western U.S., for example, has increased substantially. This biomass buildup is primarily due to the exclusion of fire and has resulted in overcrowded, overstocked stands of small-diameter and standing dead trees and other types of fiber resources. Considerable interest has recently developed in providing forest managers with tools to increase the diversity, health and sustainability of today's forests. Many of the forests in question are in a poor state of health, are susceptible to insect, disease, or fire damage or have little economic value to offset the costs of management practices to regain vigor, health or diversity.

Engineered biocomposites assembled from small pieces of wood or natural biofiber materials provide technology that is more adaptable to a changing resource base. These products can incorporate a variety of wood and natural biofiber-based raw materials in the form of fibers, particles, flakes, strands, and veneers. Composites are the tool that can both achieve resource sustainability and meet user needs in our ever-more affluent societies and for our growing populations (Winandy & Hiziroglu 2005). Composites provide the opportunity for sustainable development for both forest resources and forest-based economies because of their adaptability to a diverse array of dissimilar and widely variable resources and because of their potential to allow materials engineers to add the most value and performance over a wide array of uses/products.

Worldwide, the composites industry in 2001 exceeded 100 million cubic meters of manufactured products made in over 100 developed or developing countries. The U.S. is the single largest producer, accounting for more than 24 percent of the total world capacity. For the worldwide wood-using industry to maintain its ability to meet the needs of people for biocomposite building materials, we must continue our historic pattern of technological innovation and learn to produce highly versatile, lignocellulosic-hybrid biocomposites capable of providing reliable, predictable and cost-effective service while competing in an international cost and performance-driven market.

Engineered biocomposites must be durable, have specific properties and generally perform as expected when manufactured from a variety of natural fibrous sources alone or when wood- and/or agro-fiber-hybrids are combined with non-wood materials like cement, plastics, or fiberglass.

The fundamental research needed to accomplish these tasks will focus on understanding the relationship between performance and contribution of constituent pieces of lignocellulosic materials, ranging from veneer, flakes, particles, fibers, and flour-like materials and from the marriage of lignocellulosics and advanced high-performance materials, like Kevlar, polyamides and fiberglass. The specific challenge is to find ways of extracting more value-added composites from under-utilized low- or no-value virgin or waste biomass materials. The primary focus of the research is to develop both the fundamental understanding and the process technologies for combining different raw materials that result in naturally sustainable engineered composites for both highly specific value-added, end-use applications and for high-demand engineered composites used in a wide array of building and construction, automotive, furniture, and other uses.

The science and technology for engineering bio-based composite materials needs to be improved to (1) allow for the use of changing wood and alternative biofiber resources, (2) develop highly adaptable processes to meet consumer needs while simultaneously sustaining and improving the forest resource, and (3) continue the development of engineered structural lumber, panel composites and three-dimensional molded and/or extruded composites from small diameter, low quality timber derived from mixed species and from heretofore none usable or unthought of lignocellulosic fiber sources.

3. INTEGRATED CONVERSION TECHNOLOGY

The most efficient approach to developing a bio-based sustainable product is to use the resource solution that maximizes the added value in both a sustainable and environmentally sound manner. Biomass utilization will probably involve a series of sequential integrated processing approaches that may include an initial biorefinery stage to obtain biofuels, followed by production of bio-based products from the biorefinery residues, and then production of electrical bioenergy from bioproduct residues. Such an integrated resource solution will also offer the optimum long-term solution to meeting both user needs and sustainable development.

The concept is to choose the resource solution that maximizes to value-added derived from the biomass utilized. The pre-hydrolysis techniques is initially used to garner liquid/gas biofuels from the biomass, then the biofuel residues are used as feedstock for bio-based products such as natural biofiber composites and consumer products. Finally, the residue/residuals after bioproduct conversion are then used as feedstocks for bio-energy production (i.e., cogeneration of electricity). This three-part approach offers a unique methodology which includes using multiple biotechnologies successively so that the aggregate solution allows us to obtain higher total conversion yields and higher value-added than when using any one approach individually.

Energy is the third high volume usage component. Distributed bioenergy systems are decentralized energy production systems capable of connecting to the electrical distribution grid. Think of a large portable generator that you take with you to the woods, rather than bringing the woody biomass to the generator. Systems in the 50 Kw size are now being tested in the U.S and produce enough electrical power to run about 10 residential homes.

Systems of about one-megawatt are now being planned. A one-megawatt system uses about 12,000 tons of wood per year and could produce enough electricity to power about 200 homes. And similar to what we've stated before, if you burn the unusable logs for power, sell the merchantable logs, and sell the power to the grid, you can actually make a profit while doing forest thinning.

To achieve forest and resource sustainability we will need to economically remove millions of tons of woody biomass from the national forests to reduce the risk of catastrophic forest fires, improve forest health, and promote wildlife and recreation. Conventional forest products are not suitable outlets for most of this material. Much of it is too small and too irregular to be used for dimension lumber and the arid climate in the intermountain west makes water intensive applications like paper processing unworkable. We need a new industry that can locate in remote areas, can consume the waste biomass, and can be sized economically to function profitably not just on the material that needs to be removed now, but on the sustained growth of understory trees and shed branches that builds up in the forest when it is protected from routine fires. The product mix proposed is generally well understood and technically feasible. Oriented strand lumber is accepted as a chip based product that substitutes for dimensional lumber and offers a value-added product that can help make the integrated forest biorefinery profitable. Ethanol production, another example, is a long studied option with well-known processes and production efficiencies. However most of the effort has been on agricultural residuals or single species wood sources. Almost none of the existing literature is on the mixed species and partially decayed material that needs to be removed from the nations forests.

The saccharification processes used to produce sugars for ethanol production leave a small amount of crystalline cellulose material that is mixed in with lignin fragments and inorganic particles. The same saccharification processes are currently used to prepare cellulose nano-particles from microcrystalline cellulose. As a potential high value market, it is important to evaluate the isolation procedures required to separate this product from the other insoluble waste during the saccharification process. A readily available and reasonably priced source of nano particles is going to be needed in order for the many nano-reinforced composite products envisioned today to become realities. Nano-particles of acid resistant crystalline cellulose could provide a very high strength fiber for this market.

4. NANOTECHNOLOGY

On a volume basis, wood is the most-used material in the United States [Matos & Wagner 1998]. Wood is used extensively in housing in the United States. Over 1.9 million housing units were constructed in the United States in 2004 [ISDC 2005]. Wood-frame construction is used in almost 90% of these residential structures for a variety of reasons including cost, ease of fabrication, and the ability to produce a variety of architectural designs. On a volume basis, wood products comprise almost 80% of all materials used in residential housing in America. It is estimated that over 7×10^9 m^3 of lumber was used in structures in the United States over the last century. Half of the wood products now used in housing are engineered wood composites annually comprising over 50×10^6 m^3 of lumber, 1.85×10^9 square meters of panel products, and 195×10^6 lineal meters of I-joists.

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However—as in all markets—technology and shifting demographics give rise to changing market demands. Materials and products used in housing construction are not immune to such changes. While the basic North American wood frame home construction concept is approaching 200 years old, further wood has never achieved a significant position in non-residential construction because of perceived issues related to strength, durability, and fire safety. Thus, significant future opportunities exist for making major improvements to residential and non-residential construction. Wood and wood-based materials are facing increased competition from alternative non-wood materials. This competition with other materials has been a major driver behind recent developments in wood-based- and wood-plastic-composites. Governmental concerns for assuring resource sustainability, promoting green technologies, enhancing fire resistance, mitigating effects from natural disaster (e.g., floods, hurricanes, tornados), and other social concerns related to housing and population demographics will also come into consideration.

In the nano-tech future, today's manufacturing methods will be considered as crude and dealing with the molecular level. Nanotechnology will provide the ability to control materials at the level of atomic surfaces. Determining and altering how materials and their interfaces are constructed at nano- and atomic scales will provide the opportunity to develop new materials and products [Jones & Wegner 2005]. Because of this ability, nanotechnology represents a major opportunity for wood and wood-based materials to improve their performance and functionality develop new generations of products, and open new market segments in the coming decades. The use of Nanotechnology in Biocomposites science will lead to the development of the next generation of construction materials and building products that meet consumer demands (e.g., lower cost, more adaptable, lower maintenance, smarter) while reducing effects on the environment (e.g., energy, air, water, and waste).

Wood has the capacity to be made multifunctional and thereby be the cornerstone for advancing a biomass-based and sustainable economy [Wegner & Jones 2005a,b]. In addition, wood-based materials can be readily recycled and reused. Employing nanotechnology with wood and wood-based materials could result in previously undreamed of growth opportunities for bio-based products. Nanotechnology will result in a unique next generation of bio-products that have hyper-performance and superior serviceability. These products will have strength properties now only seen with carbon-based composites materials. These new hyper-performance bioproducts will be capable of longer service lives in severe moisture environments. Enhancements to existing uses will include development of resin-free biocomposites or wood-plastic composites having enhanced strength and serviceability because of nano-enhanced and nano-manipulated fiber-to-fiber and fiber-to-plastic bonding.

Nanotechnology presents a tool to improve structural performance and extend serviceability by orders of magnitude. Nanotechnology will help us greatly expand our ability to manipulate and control fiber-to-fiber bonding at a microscopic level, and it will also offer an opportunity to control nanofibrillar bonding at the nanoscale. Nanotechnology will allow engineers and scientists to manipulate processes and systematically eliminate the formation of random defects that now dictate the properties, performance, and serviceability of biocomposites, as we know them today. This new ability to minimize and eliminate naturally occurring and human-made internal defects will allow us to realize the true potential of bio-based materials. However, while nanocomposites will be a new frontier, nanotechnology as applied to engineered biocomposites will not be a science in itself. It will become the fundamental scale for approaching a problem, similar to how we now think of using a "material science-type" approach. Nanotechnology will become a standard for a basic type of approach to science. It will provide a tool by which we quantify or model the relation-ship between "Materials-Process-Performance".

5. SUMMARY

The utilization of engineered biocomposite materials that meet user needs and maximize the environmental sustainability is fast becoming a reality. We must commit ourselves to developing the fundamental and applied science and technology necessary to provide improved value, service-life, and utility so the world can use sustainable building materials. We propose that three critical research needs: Fundamental Biocomposite Science and Engineering, Integrated Conversion Technology using Bio-refining, Bio-based products, and Bio-energy, and Nanotechnology.

After we develop these tools, we can then apply them to address resource sustainability, enhance recyclability and minimize the environmental impacts of composite processing. Then as forest resource options change, as excess (e.g., discarded wood and fiber) waste-stream wood resources become available, as alternative non-wood and non-lignocellulosic materials become more economical and available, and as air and water quality regulations become more stringent, we will have the tools to address the problem of achieving resource sustainability and enhancing economic development through biomass utilization.

6. REFERENCES

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