Integrated Biomass Technologies:

A Future Vision for
Optimally Using

Abstract

Exciting new opportunities are emerging for sustainably meeting many global energy needs and simultaneously creating high-value bio-based consumer and construction products from wood, forest and agricultural residues, and other bio-based materials. In addition to traditional value-added bio-based products, such as lumber, paper, paperboard, and composites, opportunities are now on the horizon for biorefining to produce electricity, transportation fuels, chemical feedstocks, syngas, and nanocrystalline cellulose. In the near future, nanocrystalline cellulose, produced as a high-value by-product from the biorefining process, could likely compete with carbon fiber for use in innovative high-strength biocomposites. The holistic view of how to achieve both traditional and new high-value materials with enhanced performance properties from renewable resources is called *Integrated Biomass Technologies*. This concept promotes the use of sustainable, bio-based, environmentally neutral (or even beneficial) technologies to meet global demands for building and materials end uses, chemicals, and energy. This concept provides a systematic approach for maximizing value, performance, resource sustainability, and improving profitability in the agriculture and forest products industries.

By Jerrold E. Winandy, Alan W. Rudie, R. Sam Williams, and Theodore H. Wegner

Wood and Biomass

The agricultural sector has made significant progress in developing bio-based fuels and chemicals. Today, the dominant feedstock for ethanol transportation fuel is fermentable sugars derived from agricultural crops such as corn, rice, and sugarcane. An alternative to producing ethanol from grain or sugar crops is to use the stalks and other nonfood portions of agricultural crops as well as trees, grasses, and other herbaceous plants.

- These sources are referred to as lignocellulosics because the two dominant chemical components of the plants are cellulose, the structural polymer that represents about 50 percent of the plant material, and lignin, a cross-linked phenolic polymer that performs the role of an adhesive holding the components of the plant cell wall together (**Fig. 1**). Because plant materials form by combining CO_2 from the atmosphere with water via photosynthesis the fuels produced from them are regarded as carbon neutral, releasing into the atmosphere only the amount of CO_2 originally sequestered by the plant to produce the biomass.

- Conversion of wood to biofuels is technically feasible, but with current technology and pricing of crude petroleum, this conversion process is today only marginally economical. An integrated wood-based biorefinery concept in conjunction with the production of pulp and paper, called Value Prior to Pulping, has been proposed. An even broader version of that concept, including production of bio-based liquid transportation fuels, chemical feedstocks, and biocomposite materials, is termed Value Prior to Processing. Both are justified as means to overcome economic shortcomings by extracting maximum value from lignocellulosics through generating a wider array of products.

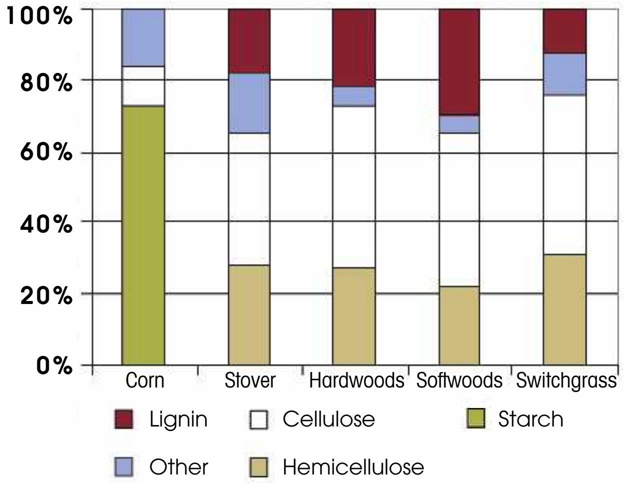


Figure 1. — Composition of typical woody lignocellulosic compared to corn grain and stover.

The general concepts of Value Prior to Pulping and Value Prior to Processing (together termed VPP) are attractive and in many cases visionary, but they do not address the entire array of issues, including in many cases the technically, environmentally, and socially problematic issues of substantively converting our global society to a bio-based, sustainable economy. This report describes a conceptual framework for a holistic approach termed "Integrated Biomass Technology."

Goals and Objectives

The *Integrated Biomass Technology* (IBT) framework lays out a vision for renewable, bio-based economies focused on producing and using bio-based products and materials, including foodstuffs, chemical feedstocks, consumer products, and construction materials (**Fig. 2**). It identifies the needs, opportunities, and research necessary to implement the concept. These include development of technologies such as:

- Initial value assessment and sorting procedures during biomass harvesting and collection,
- Direct conversion of biomass into energy,
- Biorefining some components into bio-based transportation fuels,
- Biorefining other components into chemical feedstocks,
- Processing residuals and other component materials into engineered composites, such as particleboard, fiberboard and strandboard, and paper, paperboard or advanced composites using varying combinations of biomaterials, nanomaterials, inorganic materials, and synthetics.

But most important, the IBT framework recognizes that each of the component technologies must fully integrate within existing process technologies for converting a variety of biomass types (e.g., foodstuffs and timber) into food and traditional wood products, as well as fuels/energy and an array of new high-value materials and products.

A critical part of the *Integrated Biomass Technologies* concept is that the mix of new products should be more valuable (e.g., optimal utility-energy-ecological solution and/or financial return) than the product mix from the original process(es). For example, in traditional kraft pulping, lignin and carbohydrates that are not included in the pulp are combusted to produce energy. Redirecting some portion of these two potential chemical feedstock materials to higher value products such as liquid transportation fuels, pharmaceuticals, plastics, or resins should improve the profitability of the entire process.

Globally, a vast lignocellulosic resource (biomass) is available for industrial production of materials and products, but this resource must be used in an environmentally benign, socially acceptable, and sustainable manner. Currently, traditional high-value forest product resources are in high demand as lumber, plywood, and numerous building and user products. But considerable amounts of low-value, no-value, or undervalued woody residues and biomass go unused. Common examples of currently undervalued, and often underutilized, lignocellulosic resources include suppressed-growth small-diameter timber from overstocked stands, forest residues (i.e., slash—tree tops, branches, and leaves), invasive species (e.g., salt-cedar, one-seed western juniper, and eastern red cedar), woody landfill debris, construction and demolition wood waste, comingled post-consumer recovered paper, lumber and composites; paper mill residues, and both woody and agricultural crop residues.

Implementation of an IBT strategy will allow us to:

- Develop knowledge and technologies capable of adapting to ever-changing forest-, plantation-, and agriculture-based lignocellulosic feedstocks,
- Develop and use market-driven models to identify the most profitable use of lignocellulosic resources on the basis of current market prices for various commodities,
- Modify lignocellulosic biomass conversion processing for the production of chemical feedstocks, transportation fuels, and advanced products in accordance with these market-driven models,
- Adjust raw materials and manufacturing processes to maximize the value-added product mix and product performance,
- Develop innovative products for current and new markets.

Integrated Biomass Technologies will also help forest and land managers improve forest health and condition by creating an industrial market demand for low-value biomass and thereby offset the costs associated with achieving desired forestland prescriptions. This concept can promote sustainable forest-management practices while simultaneously promoting the production and use of environmentally responsible, renewable, value-added products.

Consolidation and sorting of biomass

The initial critical component of the proposed integrated system is the recognition that each piece of woody biomass has a unique maximum value use. Technologies now exist that enable field and mill sorting of logs, branches, and other assorted biomass for optimal use. We need to further build upon this extensive knowledge base and develop cost-effective sorting techniques to target renewable biomass resources for optimal value-added use. It must also be recognized that biomass sorted for both direct conversion (direct combustion) to energy and biorefining will likely require some field processing to minimize transportation costs and maximize value.

Direct conversion of woody biomass to energy

One of the primary principles of IBT is the conversion of biomass to heat or electrical energy. It is usually less expensive to generate bio-based electrical energy locally and distribute it regionally than to transport the biomass to larger regional electrical generation facilities. The need for energy, especially bio-based energy, is growing. Recent interest in distributed small- and medium-scale electrical generation from biomass and woody waste provides new opportunities to use low- or currently no-value biomass from sorting yard operations. The forest products industry in the United States uses almost 100 million dry tons of wood waste annually for energy. A number of companies have begun, or are contemplating, installation of wood waste or hog fuel gasifiers. The producer gas resulting from this thermal decomposition can replace natural gas or be further processed to produce syngas (synthesis gas), used to manufacture other chemicals such as methanol, higher alcohols, or hydrocarbons.

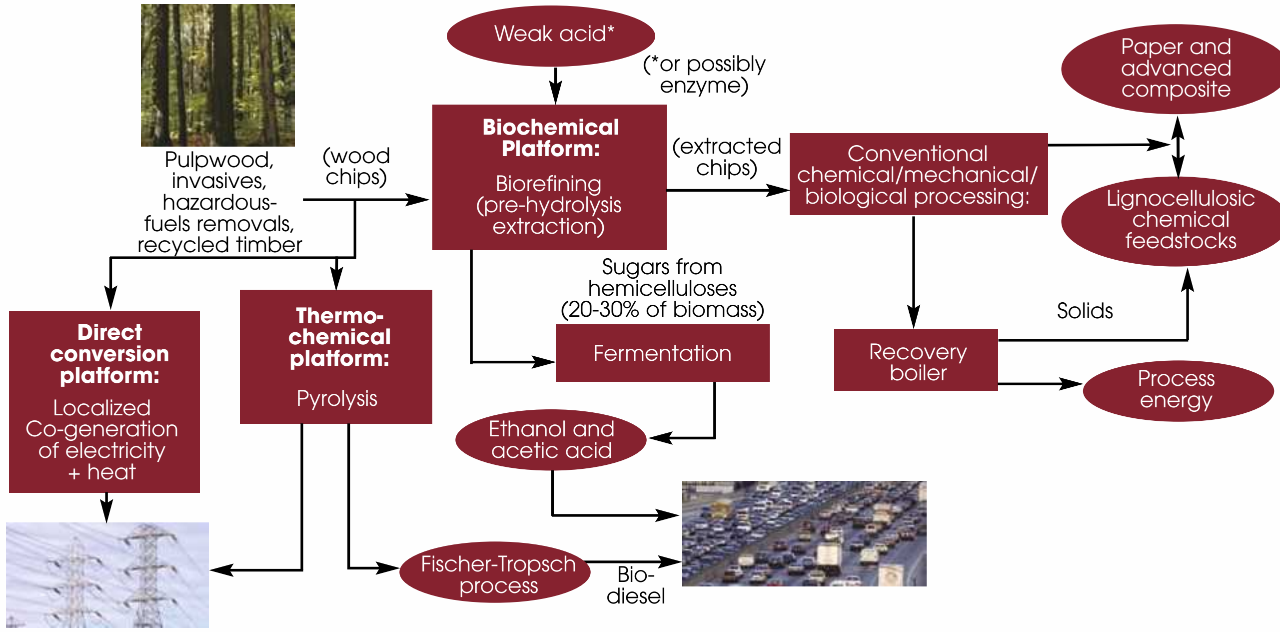
All logging operations leave forest residues that are unsuitable or too small to meet sawmill, pulp mill, panel product mill, or pole plant raw material feedstock specifications. Targeting these biomass residues for their optimal economic use will maximize the value of all currently nonmerchantable material. A number of direct conversion biomass-to-energy combustors (i.e., electrical generators) are being re-engineered to make them economical for smaller scale and even semi-portable operations. These smaller biomass-to-energy units are now available and becoming profitable alternatives to using fossil fuels. As smaller units have become available, they are being adopted by some rural communities and small businesses. Depending on size and design of the combustors, the biofuels used can be shredded material, hammer milled material, chips or pellets, but direct conversion of biomass to energy requires knowing optimal fuel sizes, moisture levels, and energy contents. In addition, some of the biofuels can be processed into pellets to meet a growing home-use market for wood pellets.

Biorefinery

Government interest in fuels from biomass is increasing, and many scientific, social, natural resource, political, and economic forces appear to be aligning to create an environment for producing transportation fuel, chemical feedstocks, and advanced biocomposite products from biomass. Thus, biorefining is another critical step in an IBT approach. Biorefining encompasses the concept of using all of the components of biomass to yield products, such as liquid transportation fuels, chemical feedstocks, pharmaceuticals, and energy. Successful biorefineries will decrease dependence on fossil fuels and reduce emission of greenhouse gases. Fuels derived from biomass are generally regarded as greenhouse gas neutral because the amount of CO_2 released upon combustion equals the amount adsorbed from the atmosphere and sequestered by the plant through photosynthesis.

Although there are many estimates of the cost to produce cellulosic ethanol, analyses suggest a cost of about US$2.15 per US gallon ($0.57/liter). The most recent cellulosic ethanol cost projections from the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) show an estimated cost of $2.25 per gallon in 2005. NREL concluded that cellulosic ethanol would be profitable at sustained oil pricing above US$50 per barrel (42 gallons) for new capacity. Investments in large pilot scale and small commercial scale demonstration cellulosic ethanol plants appear to be moving forward and should be testing this conclusion by the end of the decade.

With respect to feedstock availability, the U.S. Departments of Energy and of Agriculture estimated that 360 million dry tons of wood are available in the United



(Credit: Tivoli Gough, USDA Forest Service)

Figure 2. — Hypothetical process chart of multiple Integrated Biomass Technologies that when used selectively and progressively may optimize economic, environmental and social value for lignocellulosic biomass.

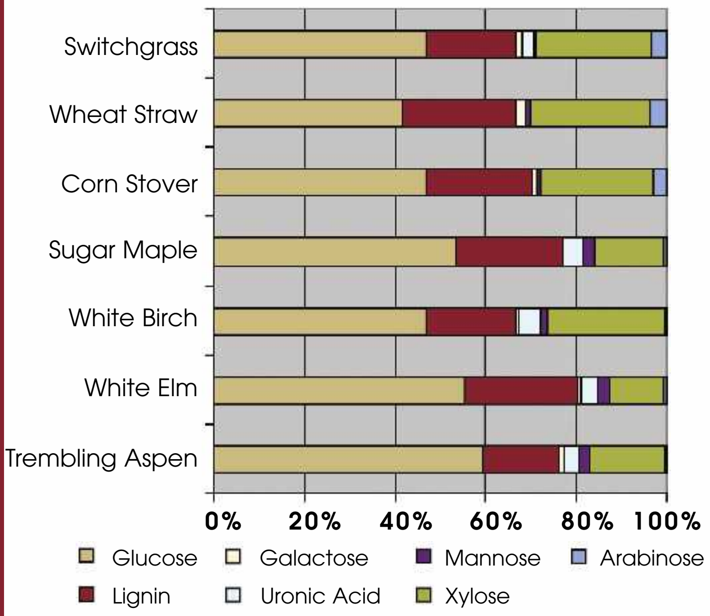


Figure 3. — Proximate composition of selected wood and agricultural species. (Sources: Timmell 1957, Pan and Sano 1999, Krull and Inglett 1980)

States on an annual basis and could be used for the production of energy (USDOE/USDA 2005). Another 600 million dry tons of agricultural residuals can be harvested without reducing the productivity of agricultural land. The cost and uncertainty associated with delivering this material to commercial biorefineries is a major factor with raw material costs projected to be greater than 50 percent of total operating costs. A primary conclusion of this joint DOE/USDA report was that by 2030 the United States could sustainably produce biofeedstocks to displace about 30 percent of our gasoline consumption.

Chemical feedstocks from biomass

Before petroleum and petroleum-based chemistries became commonplace, wood and biomass were the primary sources of chemical feedstocks providing methanol and acetic acid by destructive distillation, turpentine by steam distillation, and pine tar, rosin, and rubber. With industrial advances, petroleum and coal largely displaced wood. Today the primary use for wood is as a raw material for paper, paperboard, furniture, and building products.

Processes for converting wood and other biomass resources into liquid fuels and chemical feedstocks are again becoming cost-competitive, especially where the production of other products are already covering the costs of the raw material (e.g., value prior to pulping). Several commercial ventures now use bioplastics as binders for biodegradable thermoplastic composite products. Other developments include the use of bio-based resins to replace thermoset adhesives in engineered composites and paper and paperboard, or extracted resins for imparting moisture- or decay-resistance in nondurable wood and biocomposites.

Today there is also renewed interest in production of ethanol and other chemicals from wood. The U.S. agricultural industry already produces ethanol from corn and has intense interest in both thermal conversion and biochemical processes to make use of agricultural residuals. At present, the dominant commercial biochemical processes are fermentation of corn kernels to produce ethanol and esterification of natural bio-oils from crops for diesel fuel. The U.S. corn ethanol industry continues to expand and in 2006 produced about 5 billion gallons of ethanol and consumed about 15 percent of the total U.S. corn crop. To meet increased demand for ethanol, alternate sources of biomass such as corn stover, wheat straw, switchgrass, and wood will become necessary (USDOE 2008).

Chemical and biochemical methods

There are two major routes for producing chemicals and liquid fuels from lignocellulosic biomass (**Fig. 2**). In the biochemical route, wood is hydrolyzed into sugars using chemical and biochemical methods, with those sugars subsequently fermented to ethanol or other fermentation products such as acetic acid, butanol or 1,3-propanediol. Using thermal methods, wood can be converted to pyrolysis oil or producer gas. These products can be used directly as fuels or further processed to produce higher value products.

The two critical processes in biochemical treatment of biomass are the hydrolysis or saccharification of the carbohydrates to produce monomeric sugars, and fermentation of those sugars to produce ethanol. Increasing the yield of sugars from wood and other cellulosic materials has been a goal of researchers for many years. Fundamental research on the kinetics of hemicellulose and cellulose hydrolysis led to the "trickle-bed dilute-acid saccharification process" in 1945. It became the standard for chemical saccharification processes and was capable of providing enough sugar to produce 266 liters (approx. 70 gals) of ethanol per ton of wood (Harris et al. 1945). This process was implemented in a commercial-scale facility in Oregon during World War II but abandoned before the plant was completed as the war ended and economics changed. This concept became the basis for the U.S. Department of Energy (DOE) research on "dilute-acid hydrolysis," but this approach has now been largely abandoned in favor of "enzymatic saccharification." Enzyme manufacturers have had considerable success in accelerating the saccharification process and decreasing the costs of the enzymes, but these successes have yet to translate into improved ethanol yields or commercial processes.

Fermentation of glucose and other six-carbon sugars to ethanol is an ancient process. The hemicellulose fraction of lignocellulosic biomass also includes two five carbon sugars or pentoses (e.g., xylose and arabanose). Xylose and arabanose are considerably harder to ferment than glucose and the other six-carbon sugars. Xylose is a particularly abundant sugar in the hemicelluloses of hardwood species (from 12 to 26%) and many grasses (**Fig. 3**). There are several yeasts and bacteria capable of fermenting five-carbon sugars to ethanol, but the yield of ethanol is lower and fermentation rates are slower than obtained with industrial fermentation of glucose using yeasts like *Saccharomyces cerevisiae* or *Pichia stipitis*. Research continues on developing more industrially robust microbes to improve conversion fermentation of five-carbon sugars, and recent genetically modified organisms are showing promise (Jeffries and Jin 2004). There is much less xylose obtained in hydrolysis of softwoods (6.6%), but considerably more mannose (~10%) and galactose (~3 to 4%) (Pettersen 1984). These six-carbon hemicellulose sugars are fermented by common brewer's yeast, *S. cerevisiae*, with rates and yields with mannose approaching those obtained with glucose.

Thermochemical conversion

Thermochemical conversion methods involve rapidly heating biomass under controlled conditions in an oxygen-depleted environment to form gases, liquids, and solids (**Fig. 2**). The relative proportions of the three components depend on heating rate and temperature. In general, thermochemical conversion methods include gasification or pyrolysis, two processes in which the target product is either a gas or a liquid fuel, respectively. In either process, the goal is to convert complex heterogeneous biomass to simple chemicals. The gas phase is largely hydrogen, methane, carbon monoxide, carbon dioxide, and water. The liquid phase, or pyrolysis oil, contains thousands of compounds, many of which are unstable and polymerize (Evans and Milne 1987, Oasmaa et al. 2003). The solid phase, or char, is largely carbon. The producer gas made via gasification can be used in a gas turbine with relatively little cleanup. When producing other compounds such as liquid fuels, the carbon dioxide and water must be removed and the ratio of hydrogen and carbon monoxide adjusted using the water-gas shift reaction to optimize the yield of liquid fuels in the reforming processes. This reformulated gas mixture is generally referred to as synthesis gas or syngas.

Reforming the producer gas into hydrogen is currently the most energy efficient process, recovering 60 percent of the original biomass energy. Reforming it into methanol is slightly less efficient, recovering just 55 percent of the starting biomass energy in the product. The projected yields of transportation fuels in the NREL analysis are 291 to 437 liters per metric ton (70 to 104 gals per short ton) of biomass for ethanol and about 416 liters per metric ton (99 gals per short ton) of biomass for methanol. A similar analysis from the Netherlands also suggested that the best overall energy yields were for hydrogen and methanol. Unfortunately, hydrogen is a difficult fuel to store and transport, and the energy in methanol is just 76 percent of the heat of combustion of ethanol (Hamelinck 2004).

Use of pyrolysis oils from thermochemical processes has received a lot of attention, but the resulting liquid is corrosive and unstable. Pyrolysis oil cannot be used directly in gasoline or diesel engines but could be used directly in boilers and other combustion devices. Additional processing is necessary for transportation fuels.

	Yield	Value (m^3)
Framing Lumber	80	$81
Paper	45	$100-150
Pellets	90+	$70
Ethanol	25	$75

Table 1. — Comparison of relative value of one cubic meter of wood as lumber, paper or energy products when nom. 2- by 4-inch (38- by 89-mm) by 2.4-m is valued at $250/1000 bf, paper at $650-$975/ton, wood pellets at $240/ton and ethanol at $3.00 per gallon as of April 2008.

Fuel crop	Growth ODt/ha/a	Fuel Value GJ/ODt	Energy GJ/ha/a
Wheat	7 + 7	12.3 (straw)	123
Switchgrass	8	17.4	139
Poplar	10-15	17.3	216

Table 2. — Estimates of overall potential for yield, fuel value, and energy efficiency for various sources of biomass.

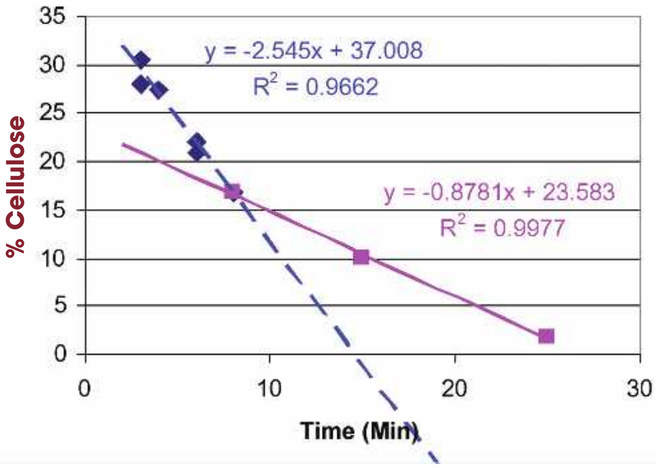


Figure 4. — Relative conversion efficiencies of amorphous cellulose (blue) and crystalline cellulose (red) (derived from: Harris et al. 1985).

Historical perspective

Much past work has focused on improving yields of fuels from biomass via exclusive production of ethanol. That work did not attempt to balance energy-input and output value based on the conversion efficiencies of hydrolyzing cellulose to glucose. It is distinctly easier to hydrolyze amorphous cellulose than crystalline cellulose (**Fig. 4**). Thus, past work did not seriously consider ethanol as just a partial component. Nor did it closely consider targeting only the most easily extracted components to achieve a profitable return on input energy followed by redirecting the remaining biomass to an array of beneficial value-added products. For example, tree species, quality and size, harvest and transportation costs, and socio-economic-environmental issues all influence the optimal IBT solution for each unique situation (**Table 1**). The concept of producing an array of value-added products and materials from biomass forms the premise of the IBT approach. In some cases that optimal solution will include wood, and in other cases that feedstock will be some other biological fiber source (**Table 2**).

In the future, as we as a society consider additional research needs, it will be critical to consider solutions within the context of such an integrated approach. In this way industry can maximize its sustainability and its profitability by producing ethanol plus an array of value-added byproducts.

Another critical consideration is process efficiency. For example, hemicellulose-derived sugars are very sensitive to acid degradation. Thus, hydrolysis of lignocellulosics is typically carried out in at least two stages. The first stage, or prehydrolysis, is usually optimized to remove as much of the hemicellulose as possible, including some of the amorphous cellulose, without excessive degradation of the remaining cellulose. The second stage, which can be either another acid hydrolysis or enzymatic saccharification, is designed to hydrolyze as much of the remaining cellulose as possible.

After about half the cellulose has been removed, acid hydrolysis enters a much slower phase because of cellulose crystallinity. At this point, the rate of degradation of already hydrolyzed sugars to hydroxymethyl-furfural and levulinic acid is similar to the rate of new sugar production.

Enzymatic saccharification also slows down once the amorphous cellulose has been hydrolyzed. With enzymes, however, the degradation reactions are no longer a major concern, and if the enzymes are allowed to continue, they are capable of hydrolyzing nearly all the cellulose in some substrates. But the retention time required to accomplish this is well beyond an economically viable process limit. The limited ability to depolymerize crystalline cellulose is the most important barrier to increasing the yield of sugars from wood hydrolysis and has been the barrier to developing a profitable wood-based ethanol process for a century or more.

Thus, the question becomes, why force the process to produce a low-value chemical like ethanol when the residual wood fiber may have greater value in other traditional uses such as paper or composites. This latter consideration has recently become especially relevant because some levels of initial hydrolytic pre-processing have been shown to actually improve the performance of engineered composite end products.

Dispersed resources/production scaling

Stand-alone thermochemical processes to produce chemicals and fuels appear to require too large a scale to fit nicely into the dispersed nature of traditional supplies of biomass. A modern pulp and paper mill handles about 2 million metric tons of dry wood annually. The largest petroleum refineries use as much as 19 million tons of crude oil in a year. This difference in supply scale seriously impedes the ability to produce hydrocarbon products competitively with the petroleum industry. An alternative approach is to produce pyrolysis oil as a higher value and higher energy density intermediate that could be shipped economically to larger conversion facilities. Pyrolysis oil has several characteristics that have prevented many direct uses, but these are less of a concern when the pyrolysis oil is intended for thermochemical decomposition to a product gas. It will still be necessary to stabilize the oil to minimize degassing and polymerization in transit, but it does not need to achieve parity with gasoline or diesel. It appears that small-scale pyrolysis units could be constructed and operated economically, but considerable work is still needed. However, operating both a pyrolysis plant and a gasification plant to perform work that could readily be carried out in one step in a gasification plant is generally not a good start to achieving profitability. Still, if the technical barriers can be overcome, this concept has the potential to surmount one of the single biggest impediments to thermochemical conversion of biomass to biofuels: lack of economy of scale due to the distributed nature of biomass.

In summary, the successful implementation of the biorefinery concept as part of IBT will: (1) promote socially acceptable sustainable development, (2) decrease global dependence on fossil fuels, (3) decrease greenhouse gases, and (4) promote sustainability of natural resource production and use. Any implementation of the IBT strategy will need to consider the full spectrum of costs, prices, and revenues. It must also consider environmental impacts and societal goals.

Advanced biocomposites

The next principle of IBT is advanced biocomposites. It involves a strategy for further advancing the development of wood and bio-based natural fiber composites on the basis of performance and sustainability. Modern wood composites technology began about 100 years ago with the development of particleboard, flakeboard, hardboard, and a variety of other wood-based composites. These products have created substantial commercial markets for value-added wood-based products in structures and furniture. Wood composite technologies are based on breaking woody material down into smaller elements, such as a veneer, particles, flakes/strands, or fiber, then reassembling these elements using an adhesive or natural fiber–fiber hydrogen bonding to create a wood-based composite product. More recently, innovative bio-based composite products using natural fibers, such as agricultural fibers or residues, or hybrid systems using combinations of both wood and natural fibers, have also become available. Youngquist et al. (1993) identified more than 1,000 citations on agricultural fiber or lignocellulosic (wood-based) composites). Globally, many lignocellulosic options exist to manufacture composites, and these options include composites employing thermoset resins, inorganic binders, or thermoplastic resins (English et al. 1997). New hybrid products, using wood- or natural fiber-plastic composites, have recently become popular for automobile components, especially door and deck panels, and for building products, such as decking, siding, roofing, fenestration, and millwork.

In North America, wood-based composites now represent more than 40 percent of the total materials used in residential construction, making them the largest single material type used in residential construction. Wood-based composites are used because they are readily available, light, strong, easily worked, and cost-effective. However, to expand into other markets, such as nonresidential and commercial construction and consumer goods, composites need to achieve enhanced performance properties, serviceability, durability, and reliability. Users of many of today's wood and wood composite products commonly refer to the same recurring issues and concerns:

- Low strength and stiffness with eventual rheological/creep problems,
- Poor durability and water-related problems,
- Limited service life,
- Limited or poor fire performance,
- Wood products harvesting and manufacturing are not currently viewed as a fully "Green Technology," and thus wood products are not being given preference in some "Green" certification programs.

Existing wood and biocomposites garner at most 10 to 20 percent of the ultimate strength and stiffness of many lignocellulosic fibers; advanced composites will greatly increase that efficiency by using cellulosic nanofibrils, nanocrystalline cellulose, and similar technologies.

Sustainable natural resource use

Characteristics of wood fibers versus agricultural fibers in biocomposites

Natural lignocellulosic-based raw materials from wood (e.g., fiber, particles, flakes, strands, and veneers) differ significantly from agricultural crops (e.g., stems, bast, leaves, seed-pods). It is desirable for lignocellulosic materials (e.g., flakes, particles, and fiber) used for composite manufacture to be uniform and consistent, but various lignocellulosic materials are known to differ widely among species. Wood fiber is usually shorter than other natural fibers. Wood fiber has cellulose content similar to fibers obtained from agricultural crops (agro-based fiber), but has higher lignin and lower pectin/extractives content (Clemons and Caulfield 2005). Pectins are complex carbohydrates with a glucouronic acid/rhamnan main-chains and rhamnan, galactan, and arabinan side-chains. For an in-depth review of the composition of lignocellulosic materials, refer to Rowell et al. (1997).

Agro-based lignocellulosics intended for use in composite products can be categorized into two types: agricultural residues and lignocellulosics grown specifically for their fiber (English et al. 1997). The residue types are characterized by species such as sugarcane bagasse, cereal straws, coconut coir, corn stover, or cotton stalks, whereas the latter is characterized by species such as jute and kenaf. For a rigorous examination of properties and processing of wood- and agro-based lignocellulosic composites, refer to Maloney (1993) or English et al. (1997), respectively.

Many nonwood agricultural fibers that are common worldwide are annual crops and are subject to seasonal availability. Harvesting is done at certain times, and production potential and infrastructure for collection, storage, drying, separating, cleaning and delivery vary widely (Clemons and Caulfield 2005, Rowell et al. 1997). The overall limitations for using agricultural lignocellulosic materials include: lack of established delivery systems, processing complications caused by fiber density and morphology, process-temperature limitations, risk of decay, and odor emission during processing and use (Clemons and Caulfield 2005). Low thermal-degrade temperatures, high volatile emissions, and high moisture absorption of agro-fibers may also limit their processing options (Rowell et al. 1997). Compared to wood fiber, agro-fibers have lower density, higher stiffness-to-weight ratio, and enhanced recyclability and biodegradability (Clemons and Caulfield 2005). Although inorganic fibers such as fiberglass are stronger, bio-fibers have a more desirable balance of strength to weight.

To successfully promote renewable, recyclable, and reusable materials, we must develop the fundamental and applied science and technology necessary to provide improved value, service-life, and utility to meet the needs of consumers for an array of sustainable materials

Transitioning to a bio-based, sustainable future

As society embraces the reality of a global economy, we must commit ourselves to promoting renewable, recyclable, and reusable materials. To successfully promote renewable, recyclable, and reusable materials, we must develop the fundamental and applied science and technology necessary to provide improved value, service-life, and utility to meet the needs of consumers for an array of sustainable materials (Winandy et al. 2005). This will require networking with international collaborators to provide a range of tools for resource managers that, regardless of resource type or quality, promote sustainability and recyclability, increase economic value-added, and reduce adverse environmental impacts.

In increasing instances, engineered wood- and biocomposites allow us to achieve resource sustainability and meet user needs across the board, from highly industrial to emerging, —and even third world—countries, many with growing populations and growing demand for materials. Wood- and biocomposite technologies provide a tool for resource managers to add value to low- or no-value bio-based resources and thereby promote demand for diverse wood and lignocellulosic feedstocks, including small-diameter timber, short-rotation plantation-grown timber, removals of invasive species, removals of hazardous forest fuels, and agricultural residues. At the same time, engineered wood composites can serve as a tool for economic development of rural communities and provide urban communities with sustainable commodity and consumer products. Biocomposite technologies also promote value-added uses for post-consumer and/or post-industrial waste materials. Resource sustainability is promoted as reuse and recyclability are enhanced and the environmental impacts of composite processing are minimized.

Engineered lignocellulosic biocomposite materials provide technology that can incorporate a variety of wood and natural lignocellulosic-based raw materials in the form of fibers, particles, flakes, strands, and veneers. However, engineered biocomposites must be developed that are durable, have higher specific performance properties and generally serve for many years regardless of end-use conditions.

Recent advances in biocomposites

Recent advances within the international wood and biocomposites research community are giving a fundamental understanding of the relationships between materials, processing, and composite end use performance properties. Advanced engineered biocomposites are currently being developed that will simultaneously meet the diverse needs of users for high-performance materials as well as economical commodity products. Recent advancements in nanotechnology will soon lead to the commercial isolation of nanocrystalline cellulose. While nanocrystalline cellulose may be only 1/10 as strong as carbon nanotubes (Xanthos 2005, Samir et al. 2005) (currently the strongest known structural material), it may cost 50 to 1,000 times less to produce (Koo 2007, Simonsen 2005). Engineered biocomposites employing nanocrystalline cellulose reinforcement could soon provide advanced performance, durability, value, service life, and utility, while at the same time being a fully sustainable technology.

A critical tool to achieve the goal of developing advanced biocomposites requires using the new science of nanotechnology to manipulate and control materials and processes at the nanoscale. Nanotechnology, once many of its apparent promises are achieved, may well present a major tool to improve structural performance and extend serviceability by orders of magnitude. Nanotechnology offers three potential opportunities for development of advanced wood- or lignocellulosic-based biocomposites:

- It is currently leading to new analytical technologies that will provide a fundamental understanding of material behavior at the nanoscale.
- It may include the incorporation of nanoparticles (inorganic and organic) into advanced biocomposites to achieve enhanced performance (**Fig. 5**).
- It may also lead to modifications of the wood and lignocellulosic raw material surfaces at the nanoscale.

This knowledge will then provide tools with which we can begin to fundamentally understand and then possibly control and manipulate critical Materials-Process-Performance relationships.

Future advances in biocomposites

The next generation of engineered biocomposites needs to provide construction materials and building products that far exceed current expectations. These next generation engineered biocomposites need to be lower cost, higher performance, more adaptable, more reliable, lower maintenance, and possess smart material properties. These advanced engineered biocomposites will:

- Develop synergistic performance by combining wood, inorganic materials, and natural biofiber,
- Provide enhanced performance and superior serviceability,
- Be more durable, dimensionally stable, moisture proof, and fire resistant,
- Possess advanced sensory capabilities for warning users when problems are imminent,
- Possess advanced biomimetic capabilities for fixing itself when problems are encountered,
- Be renewable, recyclable, and sustainable,
- Decrease environmental impacts from processing and use,
- Have both materials and processes engineered to customize and optimize performance.

To improve materials performance, meet user needs, and promote resource sustainability, we need a basic understanding of material applications, their end use-environments, and controlling economics. This understanding is needed to identify perceived problems with the performance of current-generation wood-based composites and identify unfulfilled future markets for enhanced products. It will also allow us to minimize environmental and life-cycle effects of new and reused bio-based products while also considering economic feasibility for commercial production of bio-based products.

Advanced structures

The final principle of *Integrated Biomass Technologies* is advanced structures. The concept of advanced structures is critical to a broader goal of becoming a sustainable global society. Tomorrow's structures need to outperform and outlast current systems while costing less—both economically and environmentally. Many of the materials used in advanced structures will likely be advanced biocomposites. However, advanced structures require more than just advanced materials. It is essential to develop new design approaches and a fuller understanding of the complex relationships of loads, end-use environment, and materials and systems performance.

As we move further into the 21st century, the performance demands and complexity of structures are increasing. In the past, structures were designed based solely on life safety issues. That is no longer the case. Today, structures are designed considering life safety along with functionality, environmental impact, service life, ease of maintenance and renovation, and economics/affordability. Performance-based engineering, a design approach that encompasses these considerations, was first used about two decades ago for seismic design of structures and is now gaining momentum for engineering design in many structural areas. Performance-based engineering implies design, evaluation, and construction of engineered structures and systems that meet, as economically as possible, uncertain future demands of both owner–users and the environment. The underlying premises are that performance levels and objectives can be quantified, performance can be predicted analytically, and the cost of improved performance can be evaluated so that rational trade-offs can be made on the basis of life-cycle considerations rather than construction costs alone. Performance-based engineering also requires an understanding of structural behavior under a broad spectrum of loading environments that the structure will experience. It then uses those factors to create a holistic design and assessment process relating accurate prediction of structural performance to realistic descriptions of loads and environments that the structure will experience. This approach is not just for initial design but also emphasizes monitoring the health of the structural system, evaluating performance characteristics, and identifying the need for renovation or new construction.

Our current knowledge of wood properties and structures was developed primarily through individual structural members being investigated with little consideration of their use in structural systems or interactions with environmental loading. In addition, past limitations on testing and systems-analysis prevented in-depth consideration of interacting variables in either laboratory or field environments. The widespread application of digital computing and sophisticated data acquisition and analytical systems now provides the capability to study interactions among numerous variables. As such, initial systems performance characteristics and long-term changes in those performance characteristics, especially as they related to durability within the systems, can now be examined.

Another new design criterion will further consider ancillary factors such as portability, reuse and focus on actual required life-expectancy—both long- and short-term (Winandy et al. 2006). Durability continues to be an important concern for wood- and biomass-based materials. We also need to develop remote monitoring systems that cost-effectively use sensors to indicate degradation/deterioration of wood structures applying technologies such as near infrared spectroscopy, wireless systems, and full-system nondestructive methods. These monitoring systems will evaluate performance characteristics and identify the need for renovation or deconstruction. This approach forms the foundation of strategies for cost-effectively revitalizing currently in-place infrastructure using sustainable technologies. A performance-based approach provides the appropriate framework for integration of sensing, monitoring, and control systems to monitor and maintain the health of the structure. Ultimately, smart multifunctional materials will be developed and used that respond to changing end-use conditions as they occur, take corrective actions, and provide attributes such as serving as a roof cladding while generating electricity.

Life-cycle considerations

The next generation of advanced structures will need to serve a wider array of uses and user expectations than ever before. Both long-term and short-term costs for building design, materials, and lifetime maintenance will be considered. Material costs will factor both economic issues and environmental concerns. Another explicit expectation will be usable life expectancy. This expectation will normally be primarily focused on longer life expectancies, but a new opinion now also seems to be arising about shorter life expectancies. In most future structures, designers and engineers will need to develop explicit requirements from users that clearly define issues such as intended life expectancy, future reconfiguration, retrofit, and renovation options, and end-of-life materials reuse options.

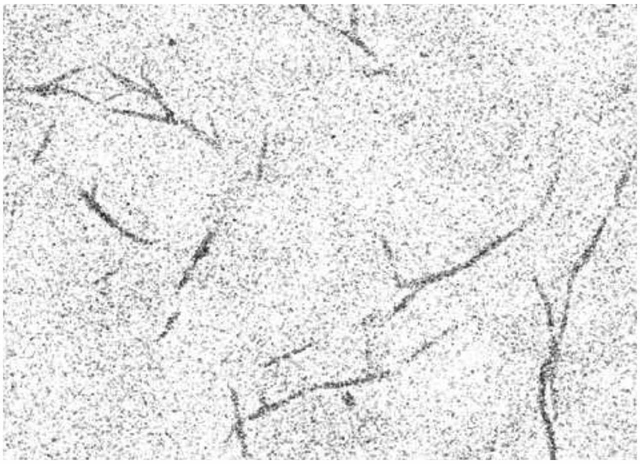


Figure 5. — Nanocrystalline cellulose-reinforced composites in thermoplastic polypropylene matrix. (Source: Sabo et al. 2006)

Structural wood design is moving to a performance-based design methodology that encompasses the entire life cycle of a structural system. Performance-based design procedures rely upon data obtained from rigorous scientific studies of multidimensional loads and systems performance. Performance-based design will initially have its greatest effect on nonresidential wood structures where owner–users can realize its long-term economic and performance benefits. Innovations and knowledge from development of a performance-based design approach will provide the framework for evaluating and minimizing both the energy and environmental footprint of sustainable structures. This approach will eventually lead to broader application and improvements in the performance and durability of residential and commercial structures.

Summary

The fundamental principles of Integrated Biomass Technologies provide a roadmap to a bio-based economy founded on the systematic use of an array of renewable forest-based and agricultural lignocellulosic resources to produce energy, liquid biofuels, chemical feedstocks, advanced biocomposites, and advanced structures. This paradigm switch to sustainably meeting user needs for energy and materials will lead to a bio-based society using renewable materials and environmentally benign technologies rather than a society based on the use of nonrenewable, nonsustainable resources.

Opportunities exist for using these technologies to achieve numerous optimal value-added, sustainable solutions for converting biomass by using a biorefinery-like approach.

They include biofuel, bio-based chemical feedstocks, bioenergy, cellulose nanofibrils, and nanocrystalline cellulose, advanced biocomposite materials, and advanced bio-based structures. IBT will allow users to add value to under- or no-value wood and lignocellulosic feedstocks such as small-diameter timber, short rotation plantation-grown timber, thinnings, agricultural fiber and lignocellulosic residues, invasive-exotic species, recycled lumber, and timber removals of hazardous forest fuels. Another potential advantage provides producers an ability to use, and adapt to, an ever-changing quality level of wood or other natural lignocellulosic feedstock. These advances will result in advanced bio-based materials and structures with improved performance relative to fire, structural integrity, and service life. The international research community has recognized this potential and is currently addressing many of these issues.

About the authors

The four authors are all senior researchers at the USDA Forest Service's Forest Products Laboratory in Madison, Wisconsin. Jerrold E. Winandy, Ph.D., is supervisory research wood scientist of the Engineered Composite Science unit. Alan W. Rudie, Ph.D., is supervisory research chemist of the Chemistry and Pulping research unit. R. Sam Williams, Ph.D., is supervisory research chemist of the Performance-enhanced Biopolymer unit. Theodore H. Wegner, Ph.D., is assistant director for Wood, Fiber and Composites research.

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