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Opportunities for using wood and biofibers for energy, chemical feedstocks, and structural applications

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10.1 Introduction

Other chapters in this book outline many exciting new opportunities for creating enhanced performance and high-value products from wood, forest residues, and other bio-based materials. In addition to traditional value-added products, such as lumber, paper, and composites, exciting new opportunities are on the horizon for biorefining to produce electricity, transportation fuels, chemical feedstocks, and cellulose nanofibers. Cellulose nanofibers, a residual from the biorefining process, will be used to manufacture innovative high-strength biocomposites necessary for advanced structures. This chapter describes *'integrated biomass technologies'*, a systematic approach for maximizing value, performance, resource sustainability, and profitability in the agriculture and forest products industries. The fundamental principles of *integrated biomass technologies* provide a global roadmap to a bio-based economy based on the systematic use of many less-desirable lignocellulosic resources to produce liquid biofuels and chemical feedstocks, advanced biocomposites, and advanced structures. This switch in approach to meeting user needs will lead to a bio-based society using sustainable technologies rather than a society based on the use of non-renewable, non-sustainable resources.

Globally, a vast lignocellulosic resource (biomass) is available for industrial use, but everyone needs to recognize that it must be used in a systematic and sustainable manner. This lignocellulosic resource includes small-diameter timber, forest residues (i.e., tree tops, branches, and leaves), high-yield plantation-grown timber (e.g., hybrid poplar), invasive species (e.g., salt-cedar, one-seed western juniper, and eastern red cedar), recycled paper, lumber and composites, and both woody and agricultural crop residues.

Integrated biomass technologies allow industry to (1) adapt to ever-changing forest and lignocellulosic feedstocks, (2) use market-driven models to determine the best use of resources on the basis of current market prices for various commodities, (3) modify production of chemical feedstocks, transportation fuels, and advanced products in accordance with these models, (4) adjust raw materials and manufacturing processes to maximize process and product performance, (5) develop new markets for innovative products, and (6) ensure that products meet structural, fire, and durability requirements for residential and commercial structures. *Integrated biomass technologies* also help forest and land managers improve forest health by working collaboratively with industry to remove less-desirable biomass and thereby offset the costs associated with efforts to restore damaged ecosystems. This further promotes sustainable forest management practices while simultaneously promoting the production and use of environmentally sensitive value-added products.

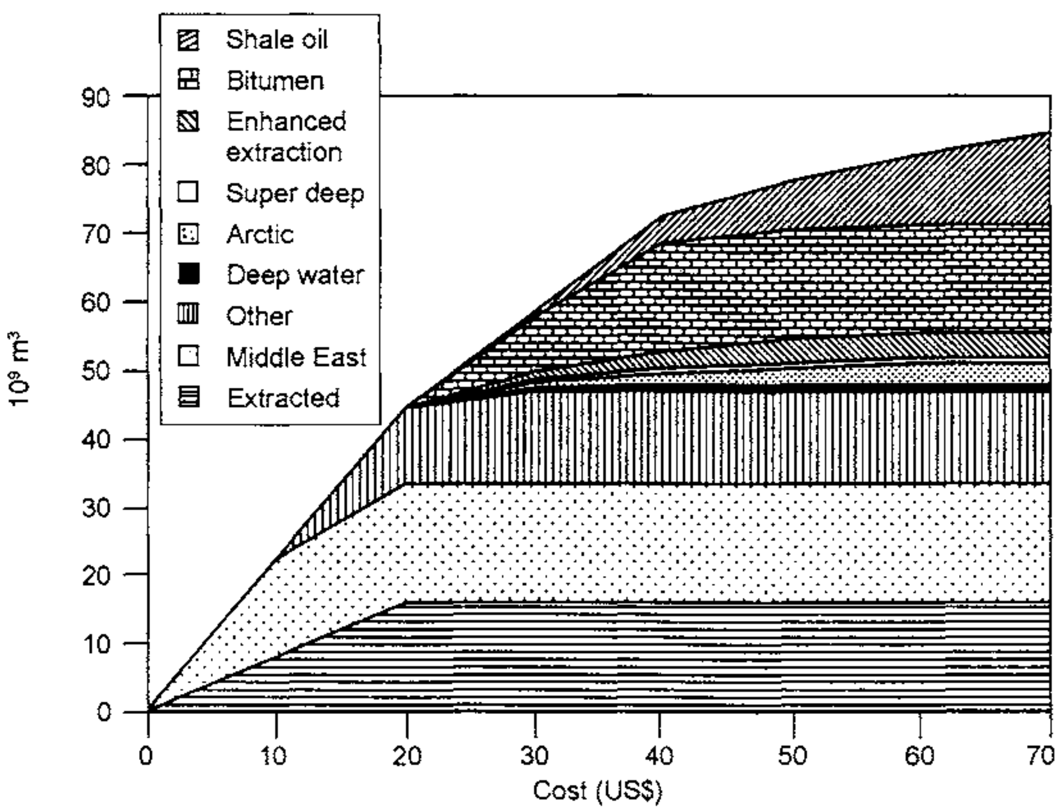
10.2 Biorefining

Biorefining is the first step in applying an *integrated biomass technologies* approach. Biorefining encompasses the use of all components of biomass to yield products, such as liquid transportation fuels, chemical feedstocks, and energy. In this section we will review the background leading to the current state of forests in North America, the fluctuations of oil prices over the past 50 years, and explore opportunities for producing transportation fuels from biomass. Biorefineries offer the potential for offsetting the cost of forest management, decreasing dependence on fossil fuels, and mitigating greenhouse gases. Fuels derived from biomass are generally regarded as greenhouse gas neutral because the amount of CO_2 released on combustion equals the amount absorbed from the atmosphere and sequestered by the plant through photosynthesis. As international concerns over global warming and greenhouse gas generation rise, government support for fuels from biomass is increasing and may give more confidence for investment in biomaterials for energy. This is an exciting time as many scientific, social, natural resource, political, and economic considerations seem to be aligning to create an environment for producing transportation fuel, chemical feedstocks, and advanced biocomposite products from biomass.

10.2.1 Past and future of petroleum

The invention of a practical internal combustion engine by Nikolaus Otto and Gottlieb Daimler in 1876 can be considered the start of the petroleum age. More than any other devices, gasoline and diesel engines have created demand for liquid fuels. Since then, every time there has been a shortage of petroleum, there have been efforts to produce ethanol from biomass. Increased demand and disruption of the supply chain created interest during the First and Second World Wars, the formation of the Organization of Petroleum Exporting Countries (OPEC) and ensuing oil embargo of 1975, and most recently, the increase in demand in Asia with supply disruptions from wars in the Middle East, all caused an increase in activity on use of biomass for energy. Unique among new incentives to develop biomass sources of energy is the current concern over global warming.

In addition to variable demand, there have long been concerns over fossil fuel reserves. The history of petroleum extraction is one of discovery and depletion. Many original oil fields were discovered because of oil leaking to the surface and most of these have long since been exhausted. By evaluating the various sources of data available on known oil reserves, a vision emerges of future supply. Known reserves continue to increase as supply companies get better at finding new oil fields and in developing new capability for extracting petroleum from deeper wells and more formidable environments. But many of these sources require higher costs to develop and only become profitable with sustained high prices (Fig. 10.1). The most recent statistics from the Energy Information Administration indicate that known reserves increased by 1% between 2006 and 2007 but production rose by just 0.035% between 2005 and 2006.[2] This difference probably reflects the increased extraction costs associated with many new reserve supplies. Still, it does not appear that the world will run out of oil in the near future. As prices rise, other sources of petroleum will become cost competitive. Considerable quantities of oil are available in heavy bitumen and oil shale. These are considered profitable at around US$25 per barrel for existing production capacity, and about US$`50 per barrel for new



10.1 Price versus availability of various crude oil reserves from different sources.[1]

capacity. Stable long-term pricing of crude oil at US$40–50/barrel will also facilitate development of alternate sources for transportation fuels. Recent price increases offer a unique opportunity to forestry and bio-based fuels industries.

The US National Renewable Energy Laboratory (NREL) has several production estimates for cellulosic ethanol. These estimates generally show profitability when oil costs between US$46 and US$60 per barrel. By comparison, the cost of ethanol from corn is US$52/barrel at current (2007) corn pricing. Although current crude oil prices are near US$50/barrel, investing in facilities to produce ethanol from biomass is tempered by concerns over a return to lower oil prices.

10.3 Energy from biomass

The concept of the forest as a source of energy and chemicals is not new. Since humans first harnessed fire, wood, and other lignocellulosic biomass it has been a source of heat, light, and power. Before petroleum and petroleum-based chemistries became commonplace, wood and biomass were the primary source of chemicals providing methanol, and acetic acid by destructive distillation, turpentine by steam distillation, and pine tar, rosin, and rubber extracted by wounding trees. With industrial advances, larger quantities and more concentrated sources of energy were required, and thus petroleum and coal largely displaced wood. Although firewood is still important in some less-developed countries, in most developed countries it is used only for residential wood stoves and, to some extent, for commercial electrical power generation. The primary use for wood is as a raw material for furniture and building products.

Once again the increased cost of fossil fuels has renewed interest in using lignocellulosics from wood and natural biofiber materials for production of both transportation fuels and chemical feedstocks. Processes for converting wood and other biomass resources into liquid fuels and chemical feedstock are now once again becoming cost competitive. One exciting ongoing development is the growing interest in development of chemical feedstocks for making bio-based plastics. This work now includes several commercial applications using bioplastics as binders for biodegradable thermoplastic composite products. Other developments include the use of bio-based resins to replace thermoset adhesives for engineered composites and paper, or extracted resins for imparting moisture or decay resistance to non-durable wood and biocomposites.

One of the primary tenants of biorefining is the conversion of biomass to energy. The forest products industry in the United States uses almost 90 million dry tonnes of wood waste annually for energy. These companies have begun installing wood waste gasifiers to convert additional biomass. The gas resulting from this thermal decomposition, especially in wood gasifier technology, is called ‘product gas’ and it can replace natural gas. There is also renewed interest in production of ethanol and other chemicals from wood. The agricultural industry already produces ethanol from corn and has intense interests in both gasification and fermentation processes to make use of the agricultural residuals. At present, the only commercial processes are fermentation of corn kernels to produce ethanol and esterification of crop oils for diesel fuel. The corn ethanol industry continues to expand and in 2006 consumed about 15% of the total US corn crop. To meet increased demand for ethanol, alternate sources of biomass will become necessary and materials such as corn stover, wheat straw, and wood are considered likely alternatives.

The US Department of Agriculture estimates that 325 million dry tonnes of wood are available in the United States on an annual basis and could be used for the production of energy.[3] Another 540 million dry tonnes 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 are major factors that determine economic feasibility. For typical biorefinery models, raw material costs are projected to be greater than 50% of total operating costs. Many site-specific factors determine the delivered price, including road infrastructure, transportation method, harvesting costs, and the quality, quantity, and type of material available.

10.4 Chemical and biochemical methods for producing fuels from biomass

There are two major routes for producing chemicals and liquid fuels from biomass. The wood can be processed into sugars using chemical and biochemical methods and the sugars are subsequently fermented to ethanol or, the wood can be converted thermochemically to pyrolysis oil or product gas and these intermediates further processed to provide liquid fuels or electricity.

Increasing the yield of ethanol 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 of ethanol per tonne of wood. This process[4] was implemented in a commercial-scale facility in Oregon during the Second World War. However, the project was abandoned before the plant was completed when the war ended. This concept became the basis for the US Department of Energy (DOE) research on ‘dilute-acid hydrolysis’ at Oak Ridge (Tennessee) and the National Renewable Energy Laboratory (NREL) at Golden, Colorado. Today, the DOE has largely abandoned this approach in favor of ‘enzymatic saccharification’. The bulk of the research throughout the 1980s and 1990s replaced the second stage of acid hydrolysis with enzymatic saccharification. Enzyme manufacturers have had considerable success in accelerating the saccharification process and reducing the costs of the enzymes, but these successes have yet to translate into improved ethanol yields or commercial processes.

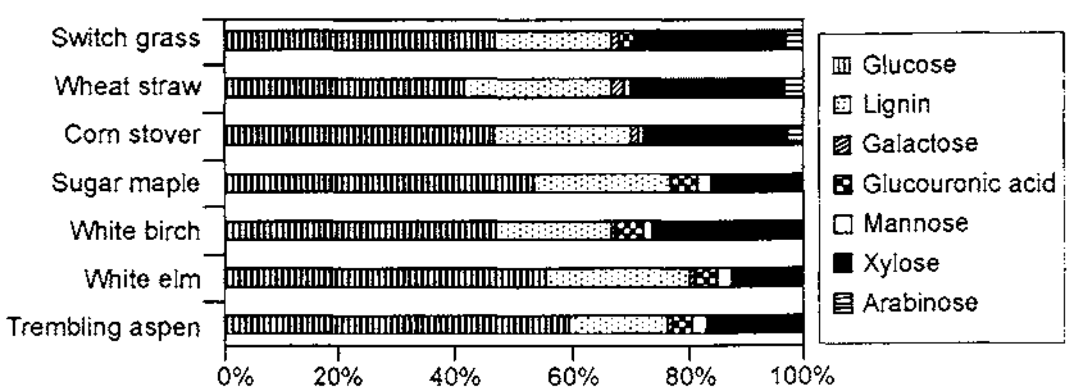
10.4.1 Enzymatic fermentation

Hardwoods and many agricultural residuals are rich in five carbon sugars or pentoses (xylose, arabanose). Xylose is a particularly abundant sugar in the hemicellulose of hardwood species (from 12% to 26%) and many grasses (Fig. 10.2). Xylose and arabinose are considerably harder to ferment than glucose and the other six carbon sugars and research continues on developing more robust organisms to improve conversion.

There is much less xylose obtained in hydrolysis of softwoods (6.6%), but considerably more mannose (10%) and the galactose and arabinose combine for another 5%.[8] Six-carbon hemicellulose sugars such as galactose and mannose are fermented by common brewer's yeast *Saccharomyces cerevisiae*, with rates and yields with mannose approaching that obtained with glucose. Pretreatment processes to remove hemicellulose can recover 50% to 90% of the available hemicellulose sugars in both hardwoods and softwoods.

10.4.2 Thermochemical methods

Thermochemical methods involve heating biomass under controlled conditions. In general, they include gasification or pyrolysis, two processes in which the target product is a gas or a liquid fuel, respectively. In either process, the goal is to convert complex heterogeneous biomass to simple chemicals. Rapid heating of wood in an oxygen-depleted environment forms gases, liquids, and solids. The relative proportion of the three components depends on heating rate and temperature. 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 over time.[9,10] The solid phase, or char, is largely carbon. The product gas produced in gasification can be used in a gas turbine with relatively little clean-up, but for 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



10.2 Proximate composition of selected wood and agricultural species.[5-7]

water gas shift reaction to optimize the yield in the reforming processes. This reformulated gas mixture is generally referred to as synthesis gas or syngas.

One of the best developed synthesis gas processes is production of methanol over Cu/ZnO catalysts. In this process, a mixture of 3:1 hydrogen:carbon monoxide is passed over a catalyst bed at high temperature and pressure. With product separation and recycle, conversion efficiencies greater than 99% can be achieved. Reforming the product gas into hydrogen is currently the most energy-efficient process, recovering 60% of the original biomass energy. Reforming it into methanol is slightly less efficient, recovering just 55% of the starting biomass energy in the product. Processes for producing other products such as longer chain length alcohols or hydrocarbons are less efficient.[11] The projected yields of transportation fuels in the NREL analysis are 291 to 437 litres per tonne of biomass for ethanol and about 416 litres per tonne 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% of the heat of combustion of ethanol.[12]

Use of pyrolysis oils from thermochemical processes has received a lot of attention, but has a number of problems that have delayed progress. Pyrolysis oil contains a complex mixture of hydrocarbons and hydroxy acids with 10–20% water. The pH is typically 1.5 to 3.0. The resulting liquid is corrosive and unstable, degassing and polymerizing on storage. Pyrolysis oil cannot be used directly in gasoline or diesel engines but can be further processed to make transportation fuels or could be used directly in boilers and other combustion devices.

10.5 Improving yields of fuels from biomass

Past research on improving yields of fuels from biomass has focused primarily on exclusive production of ethanol and did not seriously consider ethanol as a partial component as in the *integrated biomass technologies* approach. As we consider additional research needs, we believe it will be critical to consider solutions within the context of such an integrated approach. That way industry can leverage the cost of ethanol production by selling an array of by-products. Research needs and opportunities include pretreatment, value prior to processing, cellulose hydrolysis and thennomechanical methods.

10.5.1 Pretreatment

Pretreatment processes have proven to be necessary for both acid and enzymatic saccharification. Both processes are diffusion dependent, therefore wood needs to be reduced to small particle size to improve the rate at which reactants penetrate the wood and products are removed. Large molecules such as enzymes diffuse much more slowly than do small molecules. This makes the pretreatment processes used with enzymatic saccharification even more critical than for acids. The pretreatment typically involves shredding the biomass and a dilute acid or water autohydrolysis that removes the readily hydrolyzed hemicellulose and much of the amorphous cellulose.[13] Pretreatment processes that remove more of the lignin or minimize the number and size of the crystallized regions in cellulose would provide a breakthrough. Research on pretreatment is focusing on obtaining products from lignin and/or reducing cellulose crystallinity to improve saccharification yield.

10.5.2 Value prior to processing

Value prior to processing (VPP) is a pretreatment strategy with different goals from those of traditional saccharification pretreatments. VPP envisions collecting components of wood that are not critical to or maybe even in some cases detract from the eventual performance of a traditional product (such as paper or fiberboard). The collected material is subsequently used to make other products. Most of the current interest is to produce ethanol because the market is large enough to absorb the additional production without a major change in pricing. In some cases, VPP can improve the properties of the traditional product or improve the economics by decreasing overall energy consumption. Cellulose is the highest strength component of wood, therefore paper and board products require high amounts of cellulose. Cellulose concentration is increased by removing lignin and hemicellulose and these by-products are then available for other purposes.

Two proven methods have been used to remove hemicellulose: alkaline and acidic extraction. Alkaline methods extract oligomeric hemicellulose components and some small lignin fragments from the wood. They are more expensive and but tend to produce fewer unwanted by-products than acid extraction. They work best on hardwoods and result in a sugar extract that is very rich in five carbon sugars. Alkaline pretreatments have been evaluated for production of sugars and hydroxy acids.[14–17] Because many pulping processes use alkaline methods, it is envisioned that an alkaline pretreatment will still produce a high-quality paper product.

Acidic methods, including autohydrolysis, tend to hydrolyze the hemicellulose and produce sugars and low molecular weight polymers. The acid hydrolysis reaction is less selective and results in partial depolymerization of the cellulose as well. Carried too far, acid hydrolysis can also result in the formation of potentially toxic degradation products from the sugars. Acid pretreatments are used by the dissolving pulp industry and thus have a history in this application.[18] They are now being explored for the potential to make a secondary product while maintaining paper grade pulp properties.

As part of *integrated biomass technologies*, a critical advantage of VPP is that new products are more valuable than they were in the original process. In traditional kraft pulping, lignin and carbohydrates that are not included in the paper are burned to produce energy. Redirecting these chemical feedstock materials to production of higher-value products such as transportation fuels or resins may improve the profitability of the entire process. Whole-mill analysis is required to ensure that any new VPP process will be profitable.

10.5.3 Cellulose hydrolysis

Concentrated acids work very well to hydrolyze cellulose. Strong acids are cellulose solvents and because they can dissolve the cellulose as well as hydrolyze it, they can give near quantitative yields of sugars. Cellulose can be dissolved in concentrated sulfuric acid (72%) or hydrochloric acid (45%). If the temperature is low and oxygen avoided, the cellulose can be precipitated by water dilution, with relatively little degradation.[19] Strong acid conditions are also very effective at hydrolyzing lignocellulose.[20] At such conditions, the hydrolysis rate is fast enough and the temperature required low enough to avoid most of the decomposition reactions. This process proceeds relatively smoothly, leaving most of the lignin as an insoluble product. Much of the sugar remains as low molecular weight oligomers, but these are readily hydrolyzed in the diluted acid to give near quantitative yields of monomer. Concentrated acid hydrolysis has been known for over a century. But concentrated acids are expensive and energy-intensive compounds. The key technology needed to develop a viable strong acid process is acid recovery. This presents many challenges, but some recent reports suggest that engineers have successfully pilot-tested a strong acid process with acid recovery.

Dilute acid saccharification of lignocellulose proceeds at approximately three non-distinct rates. Easiest to hydrolyze are the hemicellulose polymers, which can often be removed by autohydrolysis and temperatures between 120 °C and 140°C.[21] The amorphous cellulose is hydrolyzed at a slightly slower rate. The hemicellulose sugars are very sensitive to acid degradation, and the pre-hydrolysis conditions are usually optimized to remove as much of the amorphous cellulose as possible without excessive degradation of the sugars. After about half the cellulose has been removed, hydrolysis enters a much slower phase due to cellulose crystallinity. At this point, the rate of degradation of sugars to hydroxymethyl-furfural and levulinic acid is similar to the rate of sugar production, and thus further hydrolysis is usually not justified.[21,22] Enzymatic saccharification also slows down once the amorphous cellulose has been hydrolyzed. With enzymes, the decomposition reactions are no longer a major concern so that when 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 crystallinity of 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.

10.5.4 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 is handling about 2 million tonnes of dry wood annually. The largest petroleum refineries consume as much as 17 million tonnes of crude in a year. This difference in supply scale seriously impedes the ability to produce hydrocarbon products comparatively with the petroleum industry. An alternative approach is to produce pyrolysis oil as a higher value and higher energy density intermediate that could be economically shipped to larger conversion facilities. Pyrolysis oil has several characteristics that have prevented many direct uses but these are less of a concern when the 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. There is considerable work needed to determine if small-scale pyrolysis units can be constructed and operated economically. 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 not a good start on profitability. But this concept has the potential to overcome the single biggest impediment to biofuels - the distributed nature of biomass and match the economy of scale achieved in the petroleum industry.

10.6 Technology transfer and outlook for biorefining

Obtaining high-value products from biomass prior to kraft pulping or thermomechanical pulping (TMP) continue to have strong interest in the paper industry and transfer of new biorefining technology should be easily implemented. Acid prehydrolysis liquor is commercially available from one dissolving pulp mill and at least one hardwood sulfite mill. There is growing commercial interest in prehydrolysis prior to refining for the production of newsprint grade pulps. There is also strong interest by industry for pursuing waste fuel (bark) gasifiers, evaluating gas clean-up and gas reforming technologies.

Changes in scientific, social, natural resource, political, and economic areas have created opportunities for producing transportation fuel, chemicals, and other products from biomass. As process technology emerges from this research, engineering, and economic analysis will be used to present compelling business cases for transferring this technology to industrial partners. Success in biorefining will: (1) promote sustainable social development, (2) decrease global dependence on crude oil imports, (3) decrease greenhouse gases, and (4) promote sustainability of our precious natural resources.

In summary, the success of *integrated biomass technologies* will depend on both its economic and social feasibility. Economic, environmental, and social analyses need to determine the feasibility for using various biorefinery and related biomass conversions. Any implementation of *integrated biomass technologies* will need to consider the full spectrum of costs, prices, and revenues, but it must also consider environmental impacts and societal goals.

10.7 Advanced wood and bio-based natural-fiber composites

The next tenet of *integrated biomass technologies* (advanced biocomposites) is further advancing the development of wood and bio-based natural-fiber composites on the basis of performance and sustainability. This science began with the invention of plywood by ancient Egyptians about 3000 years ago. Modem wood composites technology began about 100 years ago with the invention of particle-board, flake-board, 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 to smaller elements, such as a veneer, particle, flake/strand, or fiber, then reassembling these elements using an adhesive or natural fiber–fiber hydrogen bonding to create a wood-based composite product. More recently, new 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 identified over 1000 citations on ag-fiber or lignocellulosic composites.[23] Globally, many lignocellulosic options exist to manufacture composites and these options include composites employing thermoset resins, inorganic binders, or thermoplastic resins.[24] 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% 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 non-residential and commercial construction and consumer goods, composites need to achieve enhanced performance, serviceability, durability, and reliability. Users of many of today's wood and wood-composite products commonly refer to the same recurring problems. These common perceptions concern:

- 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 not currently viewed as a fully 'green technology' and thus are not being given preference in some 'green' certification programs;
- existing wood and bio-composites only garner 10–20% of the ultimate strength of many lignocellulosic fibers, advanced composites will greatly increase that efficiency.

Advanced wood and lignocellulosic composites are needed to meet the diverse needs of users for high-performance building and commodity products. These products need to be developed to expand beyond current saturated wood products markets and must be proven to represent the state-of-the-art in sustainable forestry and agricultural practices.

10.7.1 Sustainable natural resource use

As worldwide demand for timber and lignocellulosic resources (biomass) increase, people in resource management, government, and research must develop a shared vision with industry for long-term sustainable management of this biomass and bio-based economic development that is in concert with sustainable use of this biomass.[25] Sustainability in this context denotes a balance between conservation and use to serve local and global environmental, social, and economic needs.[26] Sustainable management of natural resources becomes more complex as increasing worldwide populations place increased demand on these resources. At present in North America, there is excess of biomass available and resurgence in commercial interest for using this resource. Composites manufactured from biomass have unique performance, particularly with regard to strength/weight ratio and offer environmental advantages to non-renewable mineral- or petrochemical-based resources.[27]

10.7.2 Characteristics of wood versus agricultural fibers in biocomposites

Natural lignocellulosic-based raw materials from wood (fibers, particles, flakes, strands, and veneers) differ from agricultural crops (stems, bast, leaves, seed-pods). It is desirable for lignocellulosic materials (flakes, particles, and fiber) used for composite manufacture to be uniform and consistent, but various lignocellulosic materials are known to differ widely among species.[24] For example, fiber from hemp is vastly different from fiber from white pine. Fiber from white pine is different from fiber from white oak. Even within the same species, growth region, growth rate, and climate affect fiber properties.[28] Wood fiber results from many years of tree growth (decades or even centuries), but they are usually shorter than other natural fibers. Wood fibers have cellulose contents similar to fibers obtained from agricultural crops (agro-based fiber), but have higher lignin and lower pectin/extractives contents (Fig. 10.2).[27] 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.*[29]

Agro-based lignocellulosics intended for use in composite products can be categorized into two types: agricultural residues and lignocellulosics grown specifically for their fiber.[24] The residue-types are characterized by species such as sugar cane bagasse, cereal straws, coconut coir, corn or cotton stalks, whereas the latter is characterized by species such as jute, kenaf, and industrial hemp. For a rigorous examination of properties and processing of wood- and agro-based lignocellulosic composites, refer to Maloney[30] or English *et al.*[24]

Many non-wood agricultural fibers that are common worldwide are usually annual crops and available seasonally. Harvesting must be done at certain times and production potential and infrastructure for collection, storage, drying, separating, cleaning, and delivery vary widely.[26,27] The overall limitations for using agricultural-based 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.[27]

Low thermal-degrade temperatures, potential for high volatile emissions, and high moisture absorption of agro-fibers may also limit processing options.[26] But compared with wood fiber, agro-fibers have lower density, higher stiffness-to-weight ratio and pliability, and enhanced recyclability and biodegradability.[26,27] Although inorganic fibers such as fiberglass have better mechanical properties, bio-fibers have desirable balance of strength and weight.[27] Natural fibers used in composites include: wood flour (i.e., used as a filler), wood particles, and fibers; short agro-fibers (i.e., used as reinforcements) and long agro-fibers such as jute, kenaf, and flax. Natural fibers with high strength and stiffness usually possess a high cellulosic content and low microfibril angle.[26]

10.7.3 Transitioning to a bio-based, sustainable future

If our society embraces the concept of a global economy, then we must commit ourselves to promoting renewable, recyclable, and reusable materials.[25] To do this, we must develop 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 consumers for a wide array of sustainable materials. This will require networking with international collaborators to provide a broad range of tools to resource managers that, regardless of resource type or quality, promote sustainability and recyclability, increase economic value-added, and reduce adverse environmental impacts.

In increasingly more instances, engineered wood- and biocomposites allow us to achieve resource sustainability and meet user needs in highly industrial, emerging, and 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, fast plantation-grown timber, removals of invasive species, removals of hazardous forest-fuels, and agricultural residues.[25] At the same time, engineered wood composites can serve as a tool for economic development of rural communities and provide urban communities with sustainable, value-added commodity and non-traditional products. Biocomposite technologies can also promote value-added uses for post-consumer and/or post-industrial waste materials.

We must develop tools to address resource sustainability by enhancing reuse and recyclability, and minimizing the environmental impacts of composite processing. Then as forest resource options change, as discarded wood and fiber from waste-streams become available, as alternative non-wood and non-lignocellulosic materials become more economical, and/or as air- and water-quality regulations become more stringent, we can adapt and sustainably address each of these issues. Engineered lignocellulosic biocomposite materials provide technology that is adaptable to a changing resource base. These products can incorporate a variety of wood and natural lignocellulosic-based raw materials in the form of fibers, particles, flakes, strands, and veneers. But engineered biocomposites must also be durable, have specific performance properties, and generally serve for many years regardless of use condition.

Whether they are manufactured from a variety of natural fibrous sources alone or combined as hybrid products with non-wood materials such as cement, ceramics, plastics, or synthetic fibers, advanced composite technologies will provide the means to engineer and produce biocomposite materials with enhanced physical and structural performance characteristics to achieve special properties. Advanced composites will further enhance our ability to meet global needs for improved performance and for value-added products that promote long-term resource sustainability. They will also decrease environmental impacts relative to those of existing non-renewable products.

10.7.4 Recent advances in biocomposites

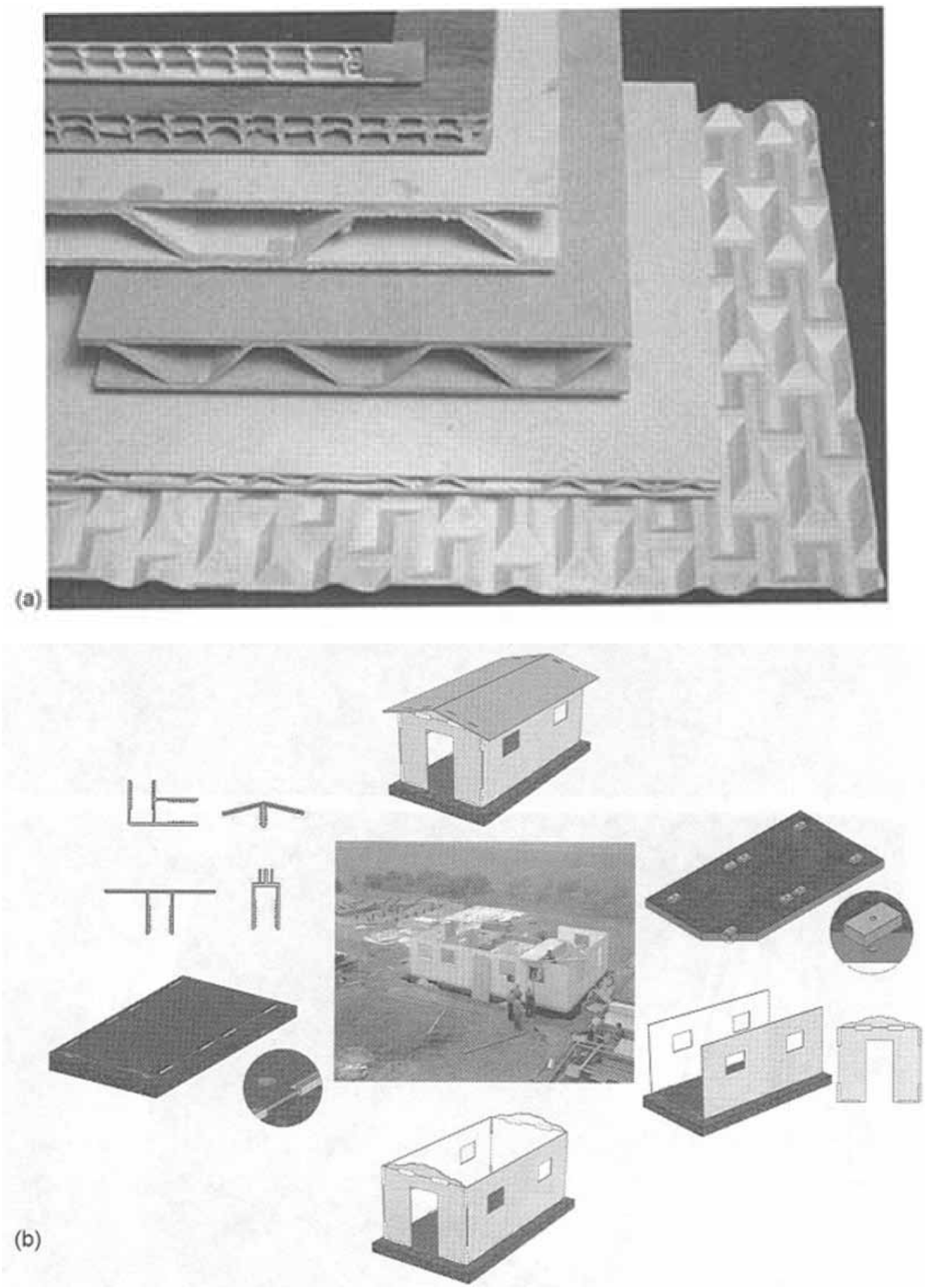
Recent advances within the international wood and biocomposites research community are just beginning to lead to the early stages of a fundamental understanding of the relationships between materials, process, and composite performance properties. These advances in science-based biocomposite processing technologies will eventually allow us to use a diverse array of bio-based raw materials and precisely control the composite manufacturing process on-the-fly. This in turn will also enable us to produce high value-added engineered biocomposites with reliable and consistent performance properties from virtually any bioresource. For example, biocomposite processing technologies allow us to use diverse species and an ever-changing quality of wood and other natural biofiber feedstocks, including small-diameter timber, fast plantation-grown timber, agricultural fiber, biofiber residues, non-desirable invasive species, and burnt timber.

Another major advance in engineered wood and biocomposites is in product and performance enhancement. Advanced engineered biocomposites are currently being developed that will simultaneously meet the diverse needs of users for high-performance and economical commodity products (Figs 10.3 and 10.4). These new engineered biocomposite products can be made from numerous bio-based feedstocks and can serve as tools to address forest management and global sustainability issues.[31,33] For another example, wood is approximately 30-40% cellulose and about half of that is crystalline cellulose. Recent advancements in nanotechnology will soon lead to the commercial isolation of nanocrystalline cellulose (Fig. 10.5). While nanocrystalline cellulose may be only one-tenth as strong as carbon nanotubes[35,36] (currently the strongest known structural material) it may cost 50–1000 times less to produce.[37,38] Engineered biocomposites employing nanocrystalline cellulose reinforcement could someday soon provide advanced performance, durability, value, service-life, and utility while at the same time being a fully sustainable technology.

10.7.5 Future advances in biocomposites

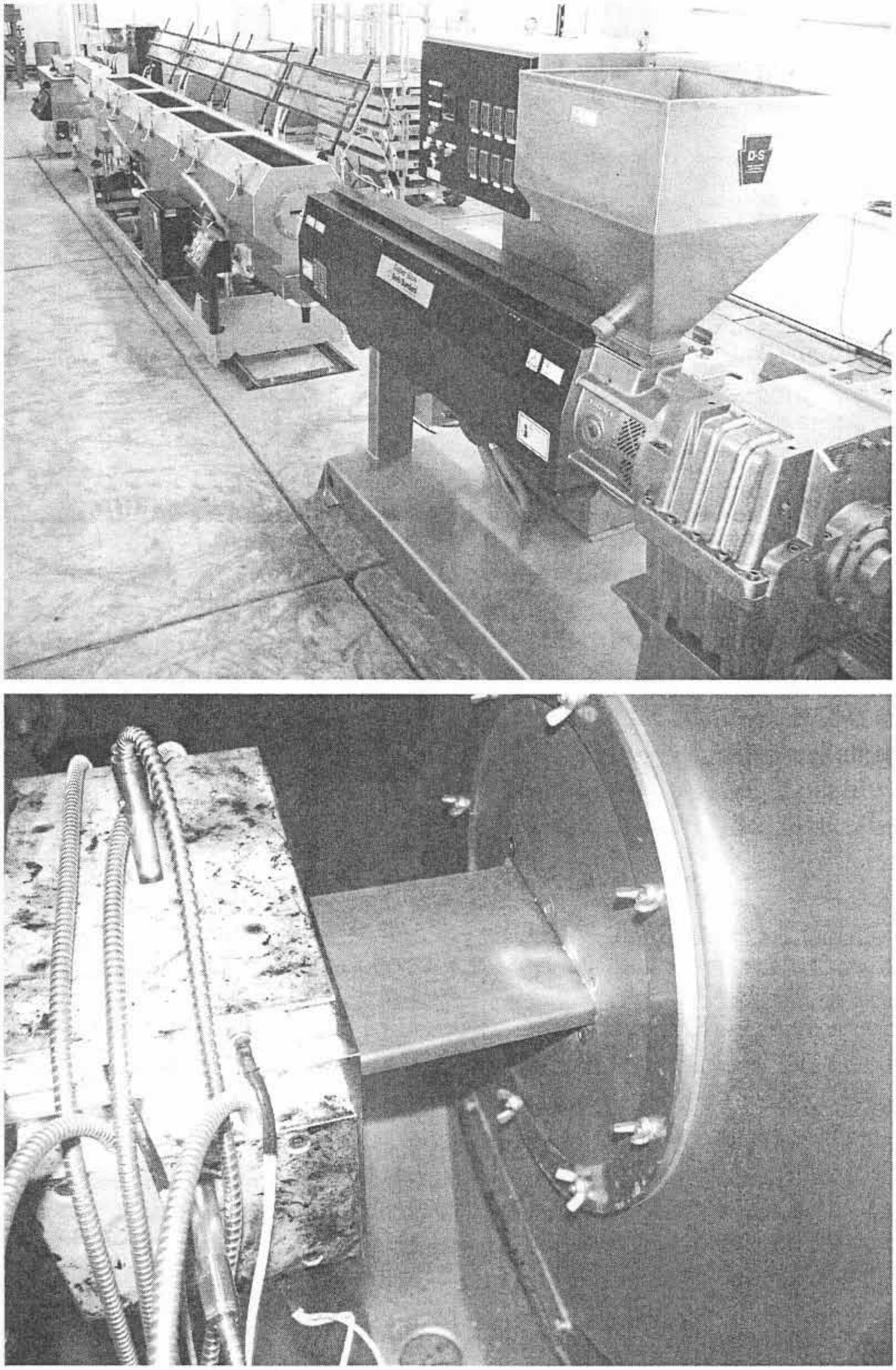
The next generation of engineered biocomposites needs to provide construction materials and building products that far exceed current expectations. They need to be lower cost, higher performance, more adaptable, more reliable, lower maintenance, and smarter. Smart materials are able to adapt to changing conditions: for example, a material that increases in porosity when it gets wet so that it dries quicker or a material that senses excess stress or strain and warns the user of the problem. It is also necessary to develop new markets (such as commercial construction, automotive, aerospace) and decrease effects on the environment. These advanced engineered biocomposites will:

- combine wood and natural biofiber for synergistic hybrid materials;
- 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:



10.3 Concept of the portable, reusable, temporary housing system: (a) using lightweight recyclable biocomposites made from virtually any bio-fiber resource and then used as (b) temporary, reusable structural building systems.[31]

- possess advanced biomemetic capabilities for fixing themselves when problems are imminent;
- be renewable, recyclable, and sustainable;
- decrease environmental impacts from processing and use; and
- have both materials and processes engineered to customize and optimize performance.



(a)

(b)

10.4 Using wood-plastic extrusion technology (a) to add value to invasive biomass used as lignocelluosic-reinforcement in thermoplastic composites (b).[32]

10.5 Nanocrystalline cellulose-reinforced composites in thermoplastic polypropylene matrix.[34]

To successfully meet these broad goals, it will be critical to collaborate and coordinate multinational, multi-partner research programs. Development of advanced engineered biocomposites will require scientific advances in chemical and materials processing. As was the case in biorefining, governments, academia, industry, and users must work together to develop a shared vision and then coordinate to systematically address a complex series research needs.

10.7.6 Research needs and opportunities

The next generation of bio-based composites gives the wood industry the opportunity for many new markets, but four research needs have been identified:

1. Enhance durability in adverse environmental or critical-use service conditions.
2. Provide higher reliability to meet the special needs of the commercial/non-residential construction market.

3. Minimize environmental life-cycle costs (resource use, energy use, emissions).
4. Address consumer needs for competitively priced products in residential and non-residential/commercial construction, furniture, and transportation systems.

Basic research is needed to increase our understanding of the relationship between performance and the contributions of constituent lignocellulosic materials, ranging from veneer, flakes, particles, fibers, and flour-like materials. We need to combine lignocellulosics with other materials such as Kevlar, polyamides, polyolefin, or fiberglass to produce advanced high-performance materials. This will also include learning to use natural nano-scale reinforcement materials, such as cellulose nanocrystals and microfibrils.

To improve the performance of materials, meet user needs, and promote resource sustainability, a basic understanding will be needed of material applications, their use-environments, and controlling economics. This understanding must identify perceived problems with the performance of current-generation wood-based composites and identify unfulfilled future markets for enhanced products. It must 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.

A critical tool to achieve these goals may require using the new science of nanotechnology to manipulate and control materials and processes at the nanoscale. Nanotechnology, if many of its apparent promises can be achieved, may present a 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. First, it is currently leading to new analytical technologies that will provide us a fundamental understanding of material behavior at the nanoscale. Next, it may include the incorporation of nanoparticles into advanced biocomposites to achieve enhanced performance (Fig. 10.5). Finally, 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 understand 'materials–process–performance' relationships. Then we may be able to exploit these three potential opportunities to identify, control, and optimize material and process factors in real time so as to engineer products having highly specified performance characteristics with both economic and environmental advantages.

We must also address our objectives for a sustainable future and advanced product using integrated approaches that simultaneously provide environmental, utilitarian. and economic advantages. It seems that a truly sustainable vision for the use of *integrated biomass technologies* is now evolving. It may include a series of sequential processing approaches including an initial biorefinery stage to obtain ethanol/biodiesel fuels either thermochemically or biochemically, followed by production of biocomposite- or paper-based products from the biorefinery residues, and then production of bio-based electrical energy from biocomposite- or paper-mill residues. Such an integrated resource solution is thought by many to offer the optimum long-term solution to meeting both user needs and sustainable development.

One of our global challenges will be to meet the needs of growing populations with biocomposites from under-utilized, low- or no-value virgin, or waste biomass materials. To accomplish this, we need to work together to advance the fundamental and applied science and technology of manufacturing engineering bio-based composite materials to:

- encourage the use of our ever-changing wood and lignocellulosic resources by providing baseline data required to allow for the optimal use;
- develop highly adaptable manufacturing processes to produce advanced biocomposite products that meet consumer needs while simultaneously empowering resource managers to sustainably manage and improve the forest resource;
- accelerate the on-going 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 previously unused lignocellulosic fiber sources.

10.7.7 Outlook for advanced biocomposites

Meeting the research needs described above for engineered biocomposite materials that meet user needs and maximize environmental sustainability will also bring economic gains to industry. If this is to be realized, 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 bio-based materials.

10.8 Advanced structures using biocomposites

The third tenet 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 out-perform and outlast current standards and all while costing less, both economically and environmentally. Many of the materials for advanced structures will probably be advanced biocomposites. But advanced structures will require more than just advanced materials. It will be essential to develop new design approaches and a fuller understanding of the complex relationships of loads, use environment, and both materials and systems performance.

10.8.1 Background

As we move further into the 21st century, the 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, and economics. Performance-based engineering, a design approach that encompasses these considerations, was first used about two decades ago for seismic design of structures and is gaining momentum for engineering design in all materials.

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 nature. The 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 cost considerations rather than construction costs alone.

Adoption of performance-based engineering concepts implies major changes in the thinking, practice, and education of designers. Perhaps most important is a shift away from dependence on empirical and experience-based conventions towards a design and assessment process. This implies a shift towards a more scientifically oriented approach with an emphasis on accurate characterization and prediction of structural performance.

Performance-based engineering requires an understanding of structural behavior under a broad spectrum of loading environments that the structure will experience. It then uses those factors to result in 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.

10.8.2 Recent advances

Our current knowledge of wood properties and structures was developed through independent technical routes; individual structural members were investigated with little consideration of their use in structural systems or interactions with environmental loading. Similarly, excellent studies on various biological agents that attack wood and potential wood preservation systems have yielded baseline information on wood deterioration and wood preservative systems, but little information exists on the potential effect of biodeterioration on structural performance. For the development of a performance-based approach, a coordinated research effort aimed at understanding the interactions of these variables is needed.

Past limitations on testing and systems-analysis prevented in-depth consideration of interacting variables in either laboratory or field environments. The widespread application of personal computers and sophisticated data acquisition and analytical systems now provide the capability to study interactions between a wide number of 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.[31]

10.8.3 Research needs and opportunities

Research supporting the development of a performance-based design approach is needed in structural analysis and modeling, durability, structural health monitoring, and life-cycle analysis.

A coordinated research effort aimed at understanding the interactions among various exposure scenarios (mechanical loads, biological agents of deterioration, moisture exposure, fire performance) is now underway to best define performance-based wood design.

Structural analysis and modeling

Structural analysis and modeling uses multidimensional models of entire systems and subsystems, extreme loading conditions, simultaneous structural and environmental loading conditions to predict performance. The studies include fasteners as critical wood design elements (load-deformation response and design criteria, failure criteria, new moment-resisting connections, structural adhesive systems), structural performance characteristics of composites in wet and humid environments, and methods for renovation and upgrade of structures (fasteners and adhesives for structural repair, remedial treatments for fungal and termite deterioration).

Durability

Durability continues to be an important concern for wood- and biomass-based materials and additional research is needed to give baseline information on performance of wood structural systems in response to moisture (properties, moisture design loads, analytical models, moisture transfer, damage accumulation functions); evaluate environmentally acceptable preservatives; and collect baseline information on performance of wood structures in response to fire. Models need to be developed to evaluate the fire performance of advanced structures at the wildland–urban interface. This includes the interaction of the various components and materials used in these advanced structures.

Structural monitoring

We need to develop remote monitoring systems that use sensors to indicate degradation of wood structures applying technologies such as near-infrared spectroscopy, wireless systems, and full-system non-destructive methods. These monitoring systems will evaluate performance characteristics and identify the need for renovation or new construction. This approach forms the foundation of strategies for revitalizing our decaying infrastructure. 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.

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 and environmental costs. Still 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 and retrofit options, and end-of-life materials reuse options.

10.8.4 Outlook for advanced structures

Performance-based design will initially have its greatest effect on non-residential wood structures where owner-users can realize its long-term benefits. Innovations and knowledge from development of a performance-based design approach will provide the framework for evaluating and minimizing the environmental footprint of wood-based structures.

The development of a performance-based design approach requires that data acquisition and analysis cannot be limited to measuring just one dependent and one independent variable. Rather it should involve simultaneous, multiple measurements that may link to a single or multiple variables. For example, monitoring the response of a structural subsystem for a single axis of loading and environmental loading might involve load and deformation measurements both in- and out-of-plane of loading, along with simultaneous temperature and moisture measurements to assess environmental loading. This entire set of data would be used to develop a comprehensive multivariate model. Experiments should be conducted at the extremes of the response spectrum so that results can be used to interpolate to common cases, instead of today’s more traditional method of extrapolation to extreme events. Economic feasibility studies of advanced structural systems will also be required.

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. Performance-based design will initially have its greatest effect on non-residential wood structures where owner-users can realize its long-term benefits. Innovations and knowledge from development of a performance-based design approach will provide the framework for evaluating and minimizing the environmental footprint of wood-based structures. Finally, advances in this approach will also lead to broader application and improvements for residential structures.

10.9 Summary

Exciting new opportunities exist for biorefining to produce biofuels, bio-based chemical feedstocks, bioenergy, and cellulose nanofibers and for developing advanced biocomposite materials, and for engineering advanced structures. This systematic approach for maximizing performance, resource sustainability, and profitability is called '*integrated biomass technologies*'. Wood and lignocellulosic technologies allow the use of diverse wood and lignocellulosic feedstocks including small-diameter timber, fast plantation-grown timber, agricultural fiber and lignocellulosic residues, invasive species, recycled lumber, and timber removals of hazardous forest-fuels. Another potential advantage provides producers an ability to use, and adapt with, an ever-changing quality level of wood and/or other natural lignocellulosic feedstocks. Still another advantage is the development of advanced bio-based materials and structures with improved performance relative to fire, structural-performance, and service-life. These engineered biocomposite products and advanced structures promote application of bio-based systems in untapped commercial and industrial construction markets. The international research community has recognized this and is currently addressing each of these issues.

From a manufacturing and a global-resource sustainability standpoint, with this evolving fundamental understanding of the relationships between materials, processes, and value/performance properties we will soon be able to recognize the attributes and quality of an array of bio-based materials then adjust our manufacturing and processing systems to produce the highest value-added solution considering an array of social, economic, natural resource, and/or political factors. Thus, as resource properties or availability changes or as economics change, the relative biofuels, biochemicals, biomaterials process streams can be modified to produce the highest value-added solution. We are now developing the technology to produce advanced, high-performance wood- and bio-fuels, -chemicals, and -materials. Then we will be able to employ those technologies as tools to help forest and land managers fund efforts to restore damaged ecosystems and that in turn may further promote sustainable forest management practices.

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