THE STATE OF ART AND FUTURE DEVELOPMENT OF BIO-BASED COMPOSITE SCIENCE AND TECHNOLOGY TOWARDS THE 21ST CENTURY

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INTRODUCTION

Bio-based resources have played a major role throughout human history. Even the earliest humans learned to use these resources to make shelters, cook food, construct tools, make clothing, keep records, and produce weapons. Collectively, society learned very early the great advantages of a resource that was widely distributed, multi functional, strong, easy to work, aesthetic, biodegradable, and renewable.

Bio-based resources are renewable, widely distributed, available locally, moldable, anisotropic, hydroscopic, recyclable, versatile, non-abrasive, porous, viscoelastic, easily available in many forms, biodegradable, combustible, compostible, and reactive. Bio-based fiber have a high aspect ratio, high strength to weight ratio, relatively low in energy conversion, and have good insulation properties (sound and thermal). The fiber structure is hollow, laminated, with molecular layers and an integrated matrix. Some might consider part of these properties as problems, such as biodegradable and combustible, but these features provide a means of predictable and programmable disposal not easily achieved with other resources.

As we approach the 21st century, there is a greater awareness of the need for materials in an expanding world population and increasing affluence. At the same time, we have an awareness that our landfills are filling up, our resources are being used up, our planet is being polluted, that non-renewable resources will not last forever, and that we need more environmentally friendly materials.

The topic of the state of art and future developments in bio-based composite science and technology area looking toward the next century has several aspects to it. First, is to look at the history of the development of bio-based composites. Secondly, is to evaluate where we are today in this science and technology and to look at research and development trends in this area which can give us some clues to future developments. Finally, to discuss what the future might look like in bio-based composites. While it is easy to write a history of a topic and even to evaluate the present state of the technology, it is very difficult to predict the future. To the extent possible, this paper will deal with the past, the present, and the future of bio-based composite science and technology as we approach the 21st century.

It is perhaps appropriate to start with some definitions. The term “bio-based resources”, as used in this paper, includes all resources that have been derived from carbon, water, and sunlight. This includes wood, agricultural crops and residues, grasses, and all other plant substances. Other terms that have been used in the literature to represent this resource including lignocellulosics, agro mass, biomass, and more recently photomass or photosynthetic mass. Bio-based resources that are of animal origin are not included such as bones, wool, proteins, fats, etc.

For this paper, a bio-based composite will be defined as any combination of two or more resources held together by some type of mastic or matrix system. Maloney (1996) defines a composite “as materials that have the commonality of being glued or bonded together”. However, using the term “material” in the definition of a composite confuses the difference between a composite and a material. In the discipline of “materials science”, a material is define as a
substance with consistent, uniform, continuous, predictable, and reproducible properties. Using this definition, bio-based resources are not true materials as they are not uniform or reproducible (Rowell 1990). A single bio-based fiber is a three dimensional polymeric composite composed mainly of cellulose in a matrix of hemicelluloses, and lignin with minor amounts of protein, extractives and inorganics.

Much of this paper will be concerned about trends in the United States as more data is available to this author about these resources. Data from other countries is included where sufficient information is available.

Cellulose is the most abundant natural polymer in the world. It is estimated that 830 million tons of cellulose are produced each year through photosynthesis (Krassig 1993). If the average plant (on a dry weight bases) contains 40% cellulose, the annual bio-based resource would be approximately 2000 million dry tons. This compares to 225 x 10^9 tons which is the estimated world reserves of petroleum and natural gas. While the bio-based resource is renewable, the petroleum and gas resources are not. We traditionally think of bio-based composites as solid, i.e. wood. As the availability of large diameter trees decreased (and the price increased) the wood industry looked to replace largeumber products and solid lumber with reconstituted wood products made using smaller diameter trees and saw and pulp mill wastes. There has been a trend away from solid wood for some traditional applications toward smaller element sizes. The new products started with very thick laminates for glue laminated beams, to thin veneers for plywood, to strands for strandboard, to flakes for flakeboard, to particles for particleboard, and, finally, to fibers for fiberboard. For the most part, all of these were made using wood. As the size of the furnish element gets smaller, it is possible to either remove defects (knots, cracks, checks, etc) or redistribute them to reduce their effect on product properties. Also, as the element size becomes smaller, the composite becomes more like a true material, i.e. consistent, uniform, continuous, predictable, and reproducible (Marra 1979). For many new bio-based composite products, the use of fibers will become more common and these fibers can come from many different agricultural sources. The traditional source of bio-based composites has been wood and for many countries, this will continue to be the major source. Wood has a higher density than annual plants so there will be more bulk when using agricultural crop fiber. There are also concerns about the seasonality of annual crops which requires considerations of harvesting, separating, drying, storing, cleaning, handling, and shipping. In the present system of using wood, storage costs can be reduced by letting the tree stand alive until needed. With any annual crop, harvesting must be done at a certain time and storage/drying/cleaning/separating will be required. This will almost certainly increase costs of using agro-based resources over wood depending on land and labor costs, however, in those countries where there is little or no wood resource left or where restrictions are in place to limit the use of wood, alternate sources of fiber are needed if there is to be a natural fiber industry in those country.

It is interesting to note how land use has changed over the years in the United States for forest and agricultural uses. In 1850, there was about 730 million acres of forests compared to about 80 million acres for agricultural crops. In 1990, the forest land mass had decreased to around 600 million acres and the agricultural crop land had increased to about 400 million acres (Doyle 1998). This means that there are more crop residues available today than there were years ago but there is still a question of harvesting and collection systems that can utilize these resources in a cost effective way. There will continue to be a competition for land not only for agricultural use but for commercial development taking the land out of agricultural production for either forest or crop use.
PAST AND PRESENT TRENDS

It is difficult to determine when the term “composite” was first used in the area of bio-based resources. All bio-based resources are themselves composites as described before so, to use the term composite using bio-based resources is to say that we have made a new composite out of an already existing composite.

If the definition of a composite is any mixture of bio-based resources glued together, then the earliest composite might have been an inorganic based brick made from straw and mud or clay. The furniture industry used veneers over solid wood several hundred years ago. What we might call the modem wood composite industry had its beginning in the late 19th century in Switzerland (Kawai 1996). A type of glue laminated beam was made for an auditorium using a casein adhesive. The world plywood industry started around 1910, the particleboard industry in the 1940’s, the hardboard industry around 1950, and the medium density fiberboard (MDF) industry in the early 1960’s.

On a historical note, it is interesting to note that on August 14, 1941, Henry Ford described what he called his “biological car” at the 15th Annual Dearborn Michigan Homecoming Day celebration (ILSR 1998). The body of this car was to be made from straw, cotton linters, hemp, flax, ramie and slash pine using a soymeal and liquid bioresm. Even though Mr. Ford’s talk was given over 50 years ago, his presentation could have been given at this Pacific-Rim Symposium and people would think that it was a new idea!

There are many different types of bio-based composites in the North American market today. They can be broken into four product types (Maloney 1996): panel products, molded products, inorganic-bonded products, and lumber and timber products. The panel products include plywood (both softwood and hardwood), blockboard, fiberboards (low density insulation board, medium density, and high density), particleboard, orientedstrandboard, and COM-PLY®. Molded products include automotive panels and door skins. Inorganic-bonded products, both cement and gypsum) include panels and roofing products. Lumber and timber products include laminated beams, laminated veneer lumber (LVL), COM-PLY® lumber, parallel strand lumber (Parallam®), oriented strand lumber (Scrimber® and TimberStrand®), and railroad ties. In general, all of these products are made using wood. The automotive panels are made using jute or flax and some particleboards are being produced using straw. There are particleboards made in other parts of the world using cotton stalks, jute, gram plant stalks (corn wheat, etc), and other plant resources.

In 1990, the Food and Agriculture section of the United Nations published a report on the world production of all wood composites made in the world (Secretariat 1990). They reported that the world wide production of wood-based panel products in 1988 was 125,883,000 M3. In 1997, Spelter et al. published inventory data on the production of wood-based panel products in the United States and Canada. Table 1 shows a summary of their data for the years 1992 and 1996. The data is presented to show trends in the composite industry in the United States and Canada.

This table shows that while plywood production has been stable from 1992 to 1996, other types of composites utilizing smaller element sizes are growing. The trend seems to be to smaller and smaller element sizes which can come from a very large variety of plants. There has been a lot of research and development going on in adhesives. Of course, the main objective is to reduce costs but there is also an effort to improve adhesion, increase performance and durability, and reduce volatile emissions. Research is being done to not only develop new adhesives but also to understand the mechanism of adhesion (interface and interphase considerations).
Table 1. Inventory of wood composite production in the United States and Canada

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood Plywood</td>
<td>17.1</td>
<td>17.0</td>
<td>1.8</td>
<td>1.8</td>
<td>18.9</td>
<td>18.8</td>
</tr>
<tr>
<td>Oriented Strandboard</td>
<td>5.9</td>
<td>8.2</td>
<td>2.0</td>
<td>4.7</td>
<td>7.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Particleboard</td>
<td>7.0</td>
<td>7.7</td>
<td>1.2</td>
<td>2.1</td>
<td>8.2</td>
<td>9.8</td>
</tr>
<tr>
<td>Medium Density Fiberboard</td>
<td>1.9</td>
<td>2.2</td>
<td>0.3</td>
<td>0.5</td>
<td>2.2</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>37.2</strong></td>
<td><strong>44.2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Research is ongoing to increase performance of bio-based composites through chemical modification. One of the most studied chemistries to improve performance properties of bio-based composites involve reactions with acetic anhydride (acetylation) (Rowell et al. 1986). Dimensional stability and biological resistance are greatly improved using this technology. Other chemicals that are going studied include epoxides, other anhydrides, isocyanates, glycols, acetals. Impregnation of composites with reactive monomers and in situ polymerization is also being done to mainly improve mechanical properties.

Research is continuing to increase the efficiency of element isolation, i.e., making strands, flakes, particles and fibers. Size, shape, orientation in the composite, surface properties, and type of resource have a big influence on the final composite performance.

**FUTURE TRENDS**

There are several trends today that can help us look into the future of bio-based composites. These include: (1) competition of resources, (2) inventory, resource selection, and sustainability, (3) recyclability and environmental issues, (4) durability and performance, (5) life cycle assessment, (6) products and production, and (7) quality assurance and testing.

(1) **Competition of Resources**

Global bio-based resources play a major role in the conversion of carbon dioxide to oxygen which is essential for human life. With the continuing debate over clean air, the need to retain a large portion of the bio-based resource, especially forests, for oxygen generation will be one of the major arguments (along with other environmental and multiple use considerations) for not cutting trees.

There will be increased competition for land use as the world population increases. In 1830, the world population was 1 billion. Over the next hundred years, it doubled to 2 billion. At the present rate of growth, the population increases by 1 billion people every eleven years. Bio-based composites provide an opportunity to fill a growing need for materials, however, there will be a greater and greater need for food and feed. One of the great future opportunities that can fill the need for food, feed, and fiber will be the use of agricultural lands to produce food and feed and the residues from these crops used for composites.

Even within the debate on land use, given that the land will be used for agricultural purposes, there will be strong competition for the resource to go into paper, textiles, and bioenergy and not be used for composites. Some of the plant residue must be left in the field for soil health.
There is a continuing debate about the use of renewable versus non-renewable resources. The future trend will favor the use of renewables but within an economic framework. Recycling will become a much more important issue and will give the non-renewable resources an argument in favor of “sustainable non-renewables” based on the reuse of these resources without significant loss of performance properties.

(2) Inventory, Resource Selection and Sustainability

There is a wide variety of bio-based resources to consider for utilization. All of them should be considered for composites to take advantage of unique properties each plant type has to offer not just because we have a desire to promote one resource over another. Unless one particular resource has some advantage in the market, it will be replaced with whatever resource has the market advantage. That market advantage can be based on many elements such as availability, price, or performance. Desire does not drive markets! Producers and manufacturers of bio-based composites must explore common interests and, where possible, prepare an enterprise-driven long range strategic plan for development and promotion of an bio-based composite industry.

Table 2 shows the inventory of some of the major sources of bio-based resources that could be utilized for composites. The data for this table was extracted from several sources using estimates and extrapolations for some of the numbers. For this reason, the data should only be considered to be a rough relative estimate of world fiber resources. The inventory of many agricultural resources can be found in the FAO database on their web at http://apps.fao.org/lim500/nph-wrap.pl?Production.Corps.Primary&Domain=S. By using a harvest index, it is possible to determine the quantity of residue associated with a given production of a crop.

Table 2 - Inventory of major potential world fiber sources

<table>
<thead>
<tr>
<th>Source</th>
<th>World (dry metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>1,750,000,000</td>
</tr>
<tr>
<td>Straw (wheat, rice, oat, barley, rye, flax, grass)</td>
<td>1,145,000,000</td>
</tr>
<tr>
<td>Stalks (corn, sorghum, cotton)</td>
<td>970,000,000</td>
</tr>
<tr>
<td>Sugar cane bagasse</td>
<td>75,000,000</td>
</tr>
<tr>
<td>Reeds</td>
<td>30,000,000</td>
</tr>
<tr>
<td>Bamboo</td>
<td>30,000,000</td>
</tr>
<tr>
<td>Cotton staple</td>
<td>15,000,000</td>
</tr>
<tr>
<td>Core (jute, kenaf, hemp)</td>
<td>8,000,000</td>
</tr>
<tr>
<td>Papyrus</td>
<td>5,000,000</td>
</tr>
<tr>
<td>Bast (jute, kenaf, hemp)</td>
<td>2,900,000</td>
</tr>
<tr>
<td>Cotton linters</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Esparto grass</td>
<td>500,000</td>
</tr>
<tr>
<td>Leaf (sisal, abaca, henequen)</td>
<td>480,000</td>
</tr>
<tr>
<td>Sabai grass</td>
<td>200,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>4,033,080,000</strong></td>
</tr>
</tbody>
</table>

Other large sources of bio-based resources can come from small diameter trees, stand improvement tree species, mixed tree species, plantation residues and thinnings, point source agricultural residues, and recycling products such as paper and paper-based products and waste
wood. Recycling paper products back into paper requires wet processing and removal of inks, inorganics, and adhesives. Recycling these same products into composites can be done using dry processing (thus eliminates a waste water stream) and all co-existing resources can be incorporated into the composite. Point source fiber sources represent resources such as rice hulls from a rice processing plant, sunflower seed hulls from an oil processing unit, and bagasse from a sugar mill.

While the data presented in Table 2 is important and interesting, it is not very useful. The data that would be useful for commercial use is the inventory of bio-based resources available within a usable distance from an existing or potential production plant. Knowing the potential resource available within a 5, 10 or 20 mile radius from a central location is the kind of data that is needed before any decisions can be made on an economic, sustainable source of raw material. As was stated before, the trend in element size is toward smaller and smaller elements and the prediction is that the fiberboard industry will be one of the fastest growing industries in the future. If that is the case, bio-based fibers will play an important role in the future of this industry. There will, however always be a need for solid wood and for composites which require large element sizes, i.e. laminated beams, plywood, strandboard, etc. These will continue to come from trees. Bio-based fibers are classified according to what part of the plant they come from. Five different fiber classifications will be used in this report: (1) bast or stem fibers, which are the fibrous bundles in the inner bark of the plant stem running the length of the stem; (2) leaf fibers, which rim the length of leaves; (3) seed-hair fibers; (4) core, pith or stick fibers, which form the low density, spongy inner part of the stem of certain plants; and (5) all other plant fibers not included above. Examples of bast or stem fibers include jute, flax, hemp, kenaf, ramie, roselle, and urena. Leaf fibers include banana, sisal, henequen, abaca, pineapple, cantala, caroa, mauritius, and phormium. Seed-hair fibers include coir, cotton, kapok, and milk weed floss. Core fibers represent the center or pith fibers of such plants as kenaf and jute and can represent over 85 percent of the dry weight of these plants. The remaining fibers include roots, leaf segments, flower heads, seed hulls and short stem fiber. While individual single fibers in all of these classes are quite short (except for flax, hemp, ramie, cotton, and kapok), fiber bundles can be quite long. For example, hemp, jute, and kenaf can have fiber bundles as long as 400 cm and abaca, mauritius, and phormium are about half this length. Considering all plant fiber types, there is a vast array of potential long and short fibers for composite production. In considering bio-based resources for composites one of the main considerations are the economics of production. As was stated before, wood has been the traditional source for many countries and that will continue in those countries that have an abundance of wood. However, even in the tree rich countries, there are discussions of using plant fiber for composites. In the United States, flax, kenaf, and corn, wheat, and rice straws are under investigation as possible sources for composites. The seasonality of these crops and the problems associated with harvesting, sorting, storage, cleaning, and transportation are major issues that have to be solved. Certainly the low bulk density of most agricultural fibers and residues are a major concern but these resources can be densitized through bailing or pelletizing. In considering a given bio-based resource for composites, fiber chemistry and properties are a major consideration. Table 3 shows the fiber dimensions and chemical composition of several different types of plant fibers (Esau 1977, Livessalo-Pfaffl 1995, Han and Rowe 1997). This type of data is critical in order to determine if a given fiber is suitable for a given composite. While this type of data exists in the literature for some types of fibers, the data is, at the best, incomplete and, at the worst, inaccurate. There needs to be a concerted effort to expand the data base to include all potential fiber sources and to standardize the testing procedure so that data from different laboratories is comparable.

In order to insure a continuous supply of bio-based resources, management of the agricultural producing land should be under a proactive system of land management whose goal is both sustainable agriculture and the promotion of healthy ecosystems. Ecosystem management
is not a euphemism for preservation, which might imply benign neglect. Sustainable agriculture denotes a balance between conservation and utilization of agricultural lands to serve both social and economic needs, from local, national and global vantage points. Sustainable agriculture does not represent exploitation but rather is aimed toward meeting all the needs of the present generation without compromising the ability of future generations to meet their needs. It encompasses, in the present case, a continuous production of bio-based composites utilizing the bio-based resources, considerations of multi-land use, and the protection, restoration, and conservation of the total ecosystem.

Table 3. Dimensions and chemical composition of some common agro-fibers

<table>
<thead>
<tr>
<th>Type of Fiber</th>
<th>Cellulose (%)</th>
<th>Fiber Dimension (mm)</th>
<th>Lignin (%)</th>
<th>Mean Length</th>
<th>Mean Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>85-90</td>
<td>0.7-1.6</td>
<td>25</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Seed Flax</td>
<td>43-47</td>
<td>21-23</td>
<td>30</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Hemp</td>
<td>57-77</td>
<td>9-13</td>
<td>20</td>
<td>0.022</td>
<td></td>
</tr>
<tr>
<td>Abaca</td>
<td>56-63</td>
<td>7-9</td>
<td>6.0</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>Coniferous wood</td>
<td>40-45</td>
<td>26-34</td>
<td>4.1</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>Sisal</td>
<td>47-62</td>
<td>7-9</td>
<td>3.3</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Bamboo</td>
<td>26-43</td>
<td>21-31</td>
<td>2.7</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>Kenaf</td>
<td>44-57</td>
<td>15-19</td>
<td>2.6</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Jute</td>
<td>45-63</td>
<td>21-26</td>
<td>2.5</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Esparto</td>
<td>33-38</td>
<td>17-19</td>
<td>1.9</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Papyrus</td>
<td>38-44</td>
<td>16-19</td>
<td>1.8</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Sugar cane bagasse</td>
<td>32-37</td>
<td>18-26</td>
<td>1.7</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Cereal straw</td>
<td>31-45</td>
<td>16-19</td>
<td>1.5</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>Corn straw</td>
<td>32-35</td>
<td>16-27</td>
<td>1.5</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>Wheat straw</td>
<td>33-39</td>
<td>16-23</td>
<td>1.4</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>Rice Straw</td>
<td>28-36</td>
<td>12-16</td>
<td>1.4</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>Esparto</td>
<td>42-54</td>
<td>17-19</td>
<td>1.2</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Deciduous wood</td>
<td>38-49</td>
<td>23-30</td>
<td>1.2</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Coir</td>
<td>35-62</td>
<td>30-45</td>
<td>0.7</td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

1 Listed by increasing mean fiber length

(3) Recyclability and Environmental Issues

Using environmentally sound technologies to make bio-based composites that are cost effective is the direction we need to go. At the present time, many of our current composites that are cost effective may not be the best from the environmental perspective and vise versa. Many companies talk about moving toward “green technologies” but this concept has yet to be clearly defined. In fact, many concepts in the environmental arena are not clearly defined or understood. For example, we use the term recyclable to mean the reuse of a resource. But what does this term mean if there is no recycling program in your area? And, if there is a recycling program, how much of a given resource is, in fact, recycled? Further, if it is recycled, what products are going to be made from that resource and how have the properties of a given product changed due to the recycle content? Many, if not most, products made today from recycled resources are more costly and have reduced performance properties as compared to the original product made using virgin resources.
We also use the term “biodegradable” as one of the advantages of using bio-based resources. A bio-based product disposed of in a modern land fill does not undergo aerobic biodegradation due to the lack of oxygen in these sealed, air tight “tombs”. So, a product can be sold as biodegradable but may never biodegrade. Even using the term “compostible” may also be misleading since it may not end up in a composting recycling program.

Another interesting aspect to using biodegradability as a promotional element in advertising is that we do not want all products to biodegrade. Certainly it is not wise to advocate the use of biodegradable structural components in airplanes, or critical components to a high rise buildings! So, biodegradability will have a place in future products but we must apply the concept where we can use it to our advantage.

There is a lot of discussion pro and con for the use of bio-based resources for energy use. While this may appear to be outside the scope of this paper, we must realize that the ultimate end point of recycling bio-based resources is composting, burning or land filling. Unless we come up with new technologies to control the degradation of the resource due to recycling, we must carefully consider the full life cycle of our bio-based composites. It is interesting that a group of people may be very much infavor of composting and strongly opposed to burning. The opposition comes from the generation of carbon dioxide from the combustion process. What they do not understand is that approximately the same amount of carbon dioxide is produced as a result of composting as is produced as a result of burning.

Burning bio-based resources is not the major concern in the global issue of carbon dioxide production. Burning bio-based resources can be considered a cyclic phenomenon. That is, the carbon dioxide produce by burning or composting bio-based resources is equal to the carbon dioxide consumed by the bio-based resource in the production of the resource. The real carbon dioxide problem is the burning of fossil fuels. The production of bio-based resources can not consume the vast amount of carbon dioxide generated by the burning of sequestered carbon millions of years old.

From the environmental stand point, one of the big issues in bio-based composite is the nature of the adhesive used. Most of the industrial adhesives used today are petroleum-based, i.e. phenol, formaldehyde, urea, isocyanates, PVA, etc. Concerns on the use of petroleum based adhesives include volatiles released in the production of composites, volatiles released in the use of composites, toxicity of resins in production, use, recycling, and disposal of composites, and costs.

Research is underway to develop new adhesive systems that are not petroleum-based, that are not, or less toxic, that are based on the use of renewable resources, and that are based on a better understand of the mechanisms of adhesion. These mechanisms require a much better understanding of interface and interphase relationships between the bio-based elements and the matrix. Some of the newest research in this area involve the use of enzymes, surface activation, biotechnology, chemical modification, and cold plasma technology.

(4) Durability and performance

We have used bio-based resources for so long that we tend to accept their performance limitations in use such as swelling, shrinking, rotting, burning, ultraviolet radiation degradation, etc. By learning to live with these limitation, we have also limit our expectations of performance, which ultimately, limits our ability to accept new concepts for improved performance and expanded markets. Bio-based composites are very familiar materials that have been used for centuries by common people for low cost, medium to low performance markets. We may have limited our expectations of bio-based composites to a time long gone while years of advances in chemistry and materials science research have been taking place.

Bio-based resources were designed, after millions of years of evolution, to perform in nature, in a wet environment. Nature is programmed to recycle these resources, in a timely way, back to basic building blocks of carbon dioxide and water through biological, thermal, aqueous, photochemical, chemical, and mechanical degradations.
One of the best ways to deal with the issue of durability of bio-based composites is to design for improved durability. In housing, this is done using large roof overhangs to minimize or prevent moisture, biological and ultraviolet degradation. In construction, bio-based composites can be placed on a durable foundation so the biocomponent does not come into direct contact with the ground. In some uses, it is not possible to solve the problem of durability by design so addition measures must be taken. In order to expand the use of agrofiber based composites in adverse environments, it is necessary to interfere with nature's recycling chemistry. We have industries that treat bio-based composites to perform better in adverse environments. Wood preservatives, fire retardants, ultraviolet energy absorbers, water repellents, paints, and coatings have all been developed to help protect bio-based composites from environmental degradation. All of these treatments are coming under attack from an environmental standpoint and new technologies need to be developed. Many of the traditional broad-spectra toxic wood preservatives are already banned or were never used in many countries. Existing technology for broad spectra toxic preservation will give way to specifically targeted toxicity and technologies that do not depend on toxicity at all. Several leachable, corrosive, and degrading fire retardants have been restricted and research in this area will be based on bound or bonded, non-hydroscopic, non-degrading fire retardants.

Research is underway to develop new concepts in bio-based composite protection. Before this is possible, it is essential we understand the mechanisms of degradation in order to derive methods to prevent them.

Table 3 shows the degradation reactions that take place when a bio-based composite is exposed in an outdoor environment. Bio-based resources are degraded biologically because organisms recognize the carbohydrate polymers (mainly the hemicelluloses) in the cell wall and have both non-specific chemical and highly specific enzyme systems capable of hydrolyzing these polymers into digestible units. Biodegradation of both the matrix and the high molecular weight cellulose weakens the fiber cell wall. Strength is lost as the matrix and cellulose polymer undergoes degradation through oxidation, hydrolysis, and dehydration reactions. As degradation continues, removal of cell wall content results in weight loss.

**Table 3 - Degradation reactions which occur when bio-based resources are exposed to nature**

<table>
<thead>
<tr>
<th>Biological Degradation</th>
<th>Enzymatic Reaction</th>
<th>Chemical Reactions</th>
<th>Mechanical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fungi, Bacteria, Insects, Termites</td>
<td>Oxidation, Hydrolysis, Reduction</td>
<td>Chewing</td>
</tr>
<tr>
<td>Thermal Degradation</td>
<td>Lightning, Sun, Man</td>
<td>Dehydration, Hydrolysis, Oxidation</td>
<td></td>
</tr>
<tr>
<td>Pyrolysis Reactions</td>
<td>Rain, Sea, Ice, Due</td>
<td>Swelling, Shrinking, Freezing, Cracking, Cyclic Wetting and Drying</td>
<td></td>
</tr>
<tr>
<td>Water Degradation</td>
<td>Ultraviolet radiation, Water, Heat, Wind</td>
<td>Oxidation, Hydrolysis</td>
<td>Erosion</td>
</tr>
<tr>
<td>Water Interactions</td>
<td>Acids, Bases, Salts, Metals</td>
<td>Oxidation, Reduction, Dehydration, Hydrolysis</td>
<td></td>
</tr>
<tr>
<td>Mechanical Degradation</td>
<td>Dust, Wind, Hail, Snow, Sand</td>
<td>Stress, Cracks, Fracture, Abrasion</td>
<td></td>
</tr>
</tbody>
</table>
Bio-based resources burn because the cell wall polymers undergo pyrolysis reactions with increasing temperature to give off volatile, flammable gasses. The hemicelluloses are the first to be thermally degraded followed closely by the cellulose polymer. The most thermally stable polymer in the cell wall is lignin. This is not surprising since oil and coal deposits are sources of prehistoric lignin. The lignin and carbohydrate components contribute to char formation, and the charred layer helps insulate the composite from further thermal degradation.

Bio-based resources change dimension with changing moisture content because the cell wall polymers contain hydroxyl and other oxygen-containing groups that attract moisture through hydrogen bonding. The hemicelluloses are mainly responsible for moisture sorption, but the accessible cellulose, noncrystalline cellulose, lignin and surface of crystalline cellulose also play roles. Moisture swells the cell wall which expands until it is saturated with water (fiber saturation point, FSP). Beyond this saturation point, moisture exists as free water in the void structure and does not contribute to further swelling. This process is reversible, and the fiber shrinks as it loses moisture below the FSP. Bio-based composites exposed to moisture frequently are not at equilibrium having wetter areas and drier areas within the same composite. This exacerbates the moisture problem resulting in differential swelling followed by cracking and/or compression set. Over the long term, bio-fiber based composites undergoes cyclic swelling and shrinking as moisture levels change resulting in more severe moisture effects than those encountered under steady moisture conditions.

Bio-based resources exposed outdoors undergoes photochemical degradation caused by ultraviolet radiation. This degradation takes place primarily in the lignin component, which is responsible for the characteristic color changes. The surface becomes richer in carbohydrate polymer content as the lignin degrades. In comparison to lignin, carbohydrate polymers are much less susceptible to ultraviolet degradation. After the lignin has been degraded, the poorly bonded carbohydrate-rich fibers erode easily from the surface, which exposes new lignin to undergo further degradative reactions. In time, this “weathering” process causes the surface of the composite to become rough and can account for a significant loss in surface fibers.

It can be seen from Table 3 that there are only four basic types of chemical reactions involved in all of the degradation reactions of bio-based resources: oxidation, hydrolysis, reduction, and dehydration. Because of the similarities in degradation chemistry, it may be possible to develop treatments that protect bio-based composites from more than one type of degradation using one type of protection system.

For protection from biological degradation, research today is directed in several areas. One is the actual mechanisms involved in the degradation pathway and ways to stop key reactions from occurring. Knowing the reactions products that develop during the degradation, it is possible to block these reactions from taking place. A second area is to concentrate on stopping the oxidation reactions from taking place which are responsible for large strength losses in bio-based composites. This involves the use of anti-oxidants to stop the initial fungal attack. Also involved in the initial fungal attack is the need of the organism to colonize. If colonization can not take place, the organism can not survive. It is also known that biological degradation occurs when the organism reduces the pH of the bio-based resource. If the buffering capacity of the resource in increased, the resistance to a lowering of pH is prevented. Finally, chemical modification of the cell wall polymers is being studied as a means of protection against biological attack. This is based on the theory that the the organism require a certain level of moisture to hydrolyze a glycosidic bond and chemical modification reduces the equilibrium moisture content (or fiber saturation point) below that required for attack (Rowe 1997).

Research in fire retardants is mainly concentrated on insolubilizing or bonding effective fire retardants into the bio-based resource. The fire retardant can also be part of the matrix structure.
Research in water repellency is concentrated on developing effective surface coatings to exclude moisture while treatments for dimensional stability are mainly in chemical reactions to bulk the cell wall to its green volume so water can not swell the composite further. High temperature steaming of bio-based resources for dimensional stability is also under investigation (Inoue et al. 1993).

Research in stabilizing bio-based composites to degradation by ultraviolet radiation is centered around stabilizing the lignin polymer since it is the cell wall component most susceptible to UV energy or by adding polymers to the cell matrix to help hold the degraded fiber structure together so water leaching of the undegraded carbohydrate polymers cannot occur. Polymer coatings that reflect UV radiation are also being developed using cold plasma modification.

Both biotechnology, which can modify bio-based resources using enzymes, and genetic engineering, which can alter plant chemistry, are exciting technologies being studied to improve durability and other performance properties of bio-based composites.

(5) Life Cycle Assessment

The bio-based resource community must do a very careful life cycle assessment to prove the assumed position of creating “environmentally friendly” products. Life cycle assessment is a process of evaluating the environmental effects associated with every aspect of a product development, use, and disposal. The environmental protection agency in the United States has developed a set of guidelines that must be used to aid in this assessment (Vigon et al. 1993). The assessment covers three basic areas: inventory analysis, impact analysis, and improvement analysis. The inventory analysis looks at the components associated with the complete process of making, using and disposal of a product. This includes growing, harvesting, processing of raw materials, manufacturing, transportation, distribution of products, and use, recycling, and disposal of all components involved in the products complete life. The impact analysis is a quantitative process to characterize and assess the energy, raw materials requirements, emissions, water, and all other considerations over the entire life-cycle of the product and all components that go into the product. The improvement analysis evaluates the opportunities to reduce the environmental impact of the entire process.

Until hard data is collected, analyzed, and presented, the industry can not prove that it uses less water, less energy, causes less pollution, has a better plan for recycling and disposal, and has a lower impact on the environment as compared to other resources. The plastics and metals industry are far ahead of the bio-based composite industries in life-cycle assessment. Some work has been done in bio-based composites and work continues but it is far from complete. There are now computer software programs to aid in the process but none of them have been perfected.

(6) Products and Production

There are many opportunities to expand existing markets and develop new markets for bio-based composites. One past trend that exists in the bio-based composite industry is that when a new product is developed, its intended market is, in many cases, to replace an existing bio-based composite. We have what might be called a bio-based composite pie. We expand the market of one bio-based composite at the expense of another bio-based composite. For example, oriented strandboard or flakeboard may be targeted to replace part of the plywood market. This does not expand the overall size of the bio-based composite pie, it only changes the size of each piece within the pie. We need to expand the whole pie! We need to start a new approach. One in which we introduce new products into markets to replace products not made from bio-based resources. We need to both reclaim last markets to plastics, metals, and other synthetics and get into markets we have never been in before.
When assessing potential markets for bio-based composites, there are two important aspects to consider: markets and products. Within each of these, there are two possible options: existing markets and new markets and existing products and new products. There are already existing products in existing markets and those will continue and, in some cases, grow. What is desired is to use an existing market to introduce a new product or go after a new market with an existing product. The greatest risk occurs when one tries to introduce a new product into a new market. This approach is much riskier but can work. To insure the most cost effective approach to the utilization of a bio-based resource, each part of a given bio-based resource should be utilized for composites for its highest potential value. In some cases, the entire plant can be used while in other cases, only part of a given plant is the desired element for the desired composite. By using the entire plant, separation processes can be eliminated which increases the total yield of plant material utilized and reduces the costs associated with fraction isolation. As was stated before, the trend in the bio-based industry is to go toward smaller and smaller elements in composites. At the fiber level, most defects in the growing plant have been eliminated so fiber-based products tend to be more homogeneous. Fibers are available from many plants so the availability of different fiber types is greatly expanded. Wood fibers come in two lengths: short and shorter. So wood fiber is limited to short fiber applications unless it is combined with longer agricultural fibers for applications in a wider array of products. There are potential products that can come from short plant fiber alone, some from long fiber bundles combined with short fibers, and some from the long fibers alone. Using all potential fibers in various combinations provides us with a new resource base to consider many new and exciting products.

There are many new product potentials to be considered for future development. Markets for existing products will expand but whole new markets are possible. The following is just a partial list of new possibilities that are mainly based on using fibers. They include: geotextiles, filters, sorbents, structural composites, non-structural composites, molded products, packaging, and combinations with other resources. Geotextiles Long bast or leaf fibers from such plants as kenaf, jute, cotton, sisal, agave, etc. can be formed into flexible fiber mats, which can be made by physical entanglement (carding), nonwoven needling, or thermoplastic fiber melt matrix technologies. In carding, the fibers are combed, mixed and physically entangled into a felted mat. These are usually of high density but can be made at almost any density. A needle punched mat is produced in a machine which passes a randomly formed machine made web through a needle board that produces a mat in which the fibers are mechanically entangled. The density of this type of mat can be controlled by the amount of fiber going through the needle board or by overlapping needled mats to give the desired density. In the thermoplastic fiber matrix, the bio-based fibers are held in the mat using a thermally soften thermoplastic fiber such as polypropylene or polyethylene. Medium- to high-density fiber mats can be used in several ways. One is for the use as a geotextile. Geotextiles derive their name from the two words geo and textile and, therefore, mean the use of fabrics in association with the earth. Geotextiles have a large variety of uses. These can be used for mulch around newly planted seedlings. The mats provide the benefits of natural mulch; in addition, controlled-release fertilizers, repellents, insecticides, and herbicides can be added to the mats as needed. Research results on the combination of mulch and pesticides in agronomic crops have been promising. The addition of such chemicals could be based on silvicultural prescriptions to ensure seedling survival and early development on planting sites where severe nutritional deficiencies, animal damage, insect attack, and weed problems are anticipated. Medium density fiber mats can also be used to replace dirt or sod for grass seeding around new homesites or along highway embankments. Grass or other type of seed can be incorporated in the fiber mat. Fiber mats promote seed germination and good moisture retention. Low and medium density fiber mats can be used for soil stabilization around new or existing construction sites. Steep slopes, without root stabilization, lead to erosion and loss of top soil. Medium and high density fiber mats can also be used below ground in road and
other types of construction as a natural separator between different materials in the layering of the back fill. It is important to restrain slippage and mixing of the different layers by placing separators between the various layers. Jute, kenaf, and flax geotextiles have been shown to work very well in these applications but the potential exists for any of the long bio-based fibers.

Filters
Medium and high density fiber mats or fiber filler containers can be used for air fibers. The density of the mats can be varied, depending on the size and quantity of material being filtered and the volume of air required to pass through the filter per unit of time. Air filters can be made to remove particulates and/or can be impregnated or reacted with various chemicals as an air freshener or cleanser. Medium to high density mats can also be used as filter aids to take particulates out of waste and drinking water or solvents.

Sorbents
Tests are presently underway to use bio-based sorbents to remove heavy metals, pesticides, and oil from rain water run off in several cities in the United States. Medium and high density mats can also be used for oil spill clean up pillows. It has been shown that bio-based core material from plants like kenaf will preferentially sorb oil out of sea water when saturated with water. There are many other potential sorbent applications of bio-fiber/core resources such as removal of dyes, trace chemicals in solvents and in the purification of solvents. It is also possible to use core materials as sorbents in cleaning aids such as floor sweep. While this is not a composite, as such, but it does represent another way bio-based resources can be used as sorbents.

Structural Composites
A structural composite is defined as one that is required to carry a load in use. In most cases, these require a thermosetting resin matrix. In the housing industry, for example, these represent load bearing walls, roof systems, subflooring, stairs, framing components, furniture, etc. In most, if not all cases, performance requirements of these composites are spelled out in codes and/or in specifications set forth by local or national organizations. Structural composites can range widely in performance from high performance materials used in the aerospace industry down to bio-based composites which have lower performance requirements. Within the bio-based composites, performance varies from multi-layered plywood and laminated lumber to low cost particleboard. Structural bio-based composites, intended for indoor use, are usually made with a low cost adhesive which is not stable to moisture while exterior grade composites use a thermosetting resin that is higher in cost but stable to moisture.

Non-Structural Composites
As the name implies, non-structural composites are not intended to carry a load in use. These can be made using a thermoplastic matrix or a thermosetting matrix and are used for such products as doors, windows, furniture, gaskets, ceiling tiles, automotive interior parts, molding, etc. These are generally lower in cost than structural composites and have fewer codes and specifications associated with them. Because of the aesthetic nature of bio-based composites, they lend themselves to products that “surround” people like wall coverings, room dividers, and furniture.

Molded Products
The present wood-based composite industry mainly produces two dimensional (flat) sheet products. In some cases, these flat sheets are cut into pieces and glued/fastened together to make shaped products such as drawers, boxes, and packaging. Flat sheet fiber composite products are made by making a gravity formed mat of fibers with an adhesive and then pressing. If the final
shape can be produced during the pressing step, then these secondary manufacturing profits can be realized by the primary board producer. Instead of making low cost flat sheet type composites, it is possible to make complex shaped composites directly using the long fibers alone or combinations of long and short fibers. In this technology, fiber mats are made similar to the ones described for use as geotextiles except during mat formation an adhesive is added by dipping or spraying of the fiber before mat formation or added as a powder during mat formation. The mat is then shaped and densified by a thermoforming step. Within certain limits, any size, shape, thickness, and density is possible. These molded composites can be used for structural or non-structural applications as well as packaging, and can be combined with other materials to form new classes of composites. This technology will be described later.

**Packaging**

Medium and high density bio-based fiber composites can be used for small containers, for example, in the food industry and for large sea-going containers for commodity goods. These composites can be shaped to suit the product by using the molding technology described previously or made into low cost, flat sheets and made into containers. Bio-based composites can and have been used for pallets where cost and weight are critical factors. Moldability has been a key factor in the development of the bio-based pallet. Bio-based fiber composites can also be used in returnable containers where the product is reused several times. These containers can range from simple crease-fold types to more solid, even nestable, types. Long bio-fiber fabric and mats can be overlayered with thermoplastic films such as polyethylene or polypropylene to be used to package such products as concrete, foods, chemicals, and fertilizer. Corrosive chemicals require the plastic film to make them more water resistant and reduce degradation of the bio-based fiber. There are also many applications for bio-based fiber as paper sheet products for packaging. These vary from simple paper wrappers to corrugated, multi-folded, multi-layered packaging.

**Combinations with Other Resources**

It is possible to make completely new types of composites by combining different resources. It is possible to combine, blend, or alloy leaf, bast and/or stick fiber with other materials such as glass, metals, plastics, and synthetics to produce new classes of materials. The objective will be to combine two or more materials in such a way that a synergism between the components results in a new material that is much better than the individual components. Bio-based fiber/glass fiber composites can be made using the glass as a surface material or combined as a fiber with bio-based fiber. Composites of this type can have a very high stiffness to weight ratio. The long bast fibers can also be used in place of glass fiber in resin injection molding (RIM) or used to replace, or in combination with, glass fiber in resin transfer molding (RTM) technologies. Problems of dimensional stability and compatibility with the resin must be addressed but this could also lead to new markets for property enhanced bio-based resources. Metal films can be overlaid on to smooth, dimensionally stabilized fiber composite surfaces or applied through cold plasma technology to produce durable coatings. Such products could be used in exterior construction to replace all aluminum or vinyl siding, markets where bio-based resources have lost market share. Metal fibers can also be combined with stabilized fiber in a matrix configuration in the same way metal fibers are added to rubber to produce wear-resistant aircraft tires. A metal matrix offers excellent temperature resistance and improved strength properties, and the ductility of the metal lends toughness to the resulting composite. Application for metal matrix composites could be in the cooler parts of the skin of ultra-high-speed aircraft. Technology also exists for making molded products using perforated metal plates embedded in a phenolic-coated fiber mat, which is then pressed into various shaped sections. Bio-fibers can also be combined in an inorganic matrix. Such composites are dimensionally and thermally stable, and they can be used as
substitutes for asbestos composites. Inorganic bonded bast fiber composites can also be made with variable densities that can be used for structural applications. One of the biggest new areas of research in the value added area is in combining natural fibers with thermoplastics. Since prices for plastics have risen sharply over the past few years, adding a natural powder or fiber to plastics provides a cost reduction to the plastic industry (and in some cases increases performance as well) but to the bio-based industry, this represents an increased value for the bio-based component. Blending of the plastics with the bio-based fibers may require compatibilization to improve dispersion, flow and mechanical properties of the composite. Extrusion of bio-based filled plastics for the automotive industry is well known and has been used for more than twenty years. Typical blending involves the plastic-filler/reinforcement to be shear mixed at temperatures above the softening point of the plastics. The heated mixture is then typically extruded into “small rods”, that are then cut into short lengths to produce a conventional pellet. The pellets can then be used in typical injection or compression molding techniques. To reduce the cost of this blending process, direct injection molding of bio-fiber/plastics can be done. The direct injection molding process probably has limitations on the amount of filler/fiber that can be used in the composite, and is also likely to be limited to particulate or shorter fiber. The chemical characteristics of the surface and bulk of the bio-fibers are also important in the blending with plastics. The ability of the matrix of the lignocellulosic (hemicellulose and lignin) to soften in the presence of moisture at plastic processing temperature may give these materials unique characteristics to develop novel processing techniques.

The primary advantages of using bio-based fibers as fillers/reinforcements in plastics are low densities, non-abrasive, high filling levels possible resulting in high stiffness properties, high specific properties, easily recyclable, unlike brittle fibers, the fibers will not fracture when processing over sharp curvatures, biodegradable, wide variety of fibers available throughout the world, would generate rural jobs increases non-food agricultural/farm based economy, low energy consumption, and low cost.

Material cost savings due the incorporation of the relatively low cost bio-fibers and the higher filling levels possible, coupled with the advantage of being non-abrasive to the mixing and molding equipment are benefits that are not likely to be ignored by the plastics industry for use in the automotive, building, appliance and other applications.

This is just a few of the potential expanded or new products that can be produced from a wide variety of bio-based fibers. Another area to consider for expanding new products, are new ideas in production.

In most cases in the Western world, bio-based composite production units are very large. This is based on the economy of scale and the fact that most existing bio-based composite industry are based on high volume sales. Future mills, in many countries will be smaller production plants with the possibility of mobile units that can be moved to a given production site. Equipment for these smaller mills will be made within that country using indigenous materials and local labor. The cost of importing new, and in some cases, used equipment from Western countries is prohibitive for most developing countries.

(7) Quality Assurance and Testing

There is a need to develop an assurance of quality in the use of bio-based products in world markets especially where they are replacing traditional products made from other resources. This requires the need to develop codes and specification of each desired bio-based composite product. In some local markets around the world, there may be no or zero code requirements at the present time. In order to assure the user of the composites that the product will perform in a certain way, codes should be developed to insure consumer confidence. Certainly for international markets, there will be a need to follow codes and specifications for the intended country. Without this, there is no hope of entering that country’s markets with a new
bio-based composite material. There is a need for research on properties and performance of each type of proposed composite product. Research, however, can go on forever but, in most cases, there is not enough data to convince industry to start using a new resource over the one they presently use. Research can just push so far to get a new product into the market. At some point the market must pull the technology into use. There are many examples where there has been a strong research push but no market pull and so the technology remains in the research arena. We need to expand and standardize our testing program on both chemical and physical properties of bio-based resources and composites made from them. We need to keep up with new experimental techniques that are being developed in other materials areas and utilize these new innovations to expand our knowledge base of our composite materials. We also need to establish a meaningful link between accelerated aging tests and the “real world”. Many of the tests done in the laboratory are intended to speed up the time frame to failure of a given composite in a given environment but we have little understanding of exactly how much time the test represents in the world in which the composite will be expected to perform.

CONCLUDING THOUGHTS

The future of bio-based composites will be very exciting and dynamic. It will be driven by traditions, trends, costs, performance, availability of resources, and legislation. Of these, the most critical issue is costs. Logical, creative and futuristic ideas will have little chance of success if the economics are not positive. In the area of bio-based resource utilization, there are several competing ideologies today that are driving public opinion. On the one hand we have a growing need to create jobs, expand recreational opportunities, and improve the standard of living. On the other hand, we have concerns about energy consumption an expanding world population maintaining wilderness areas, cleaning up the environment and the consumption of our natural resources. There is no “right or simple” answer. There is no question that renewable, recyclable, and sustainable resources will play a major role in future world developments. Bio-based resources and bio-based composites will be part of this dynamic future. We must not allow ourselves to be locked into a mental framework tied to past technologies or close our eyes to exciting new possibilities.

By considering the entire bio-based resource as a raw material for bio-based composites, we are not limited to just one type of bio-based resource. Wood will remain the major raw material for many bio-based composites for those countries that have an abundant wood supply and where wood remains economic. Countries with limited or no wood supplies will rely more and more on non-wood bio-based resources. The world is full of many varieties of renewable bio-based resources and only a few of them are now being used for composites.

Existing bio-based composite markets will continue to grow but the real excitement will come in the new potential markets we have either lost to other resources or in totally new markets. We are no longer limited by shape, density, size, or texture. We are only limited by our imagination and our knowledge and understanding of how to achieve the highest level of performance from these bio-based composites.

We must interact in the materials community to develop our true place in the materials world. As in all competitions, there will be a natural selection process in materials usage where the survival of the fittest will be the resource that has the most to offer in a cost effective and environmental framework. We must lead market development not simply react to consumer needs. We must not only continue to make incremental improvements in present technology but develop whole new technologies that take one of the oldest resources into a leadership position in composites into the 21st century. The 21st century may well be known as the cellulosic era. We can put our collective hands in our pockets and lament the passing of the “good old days” or we can put our collective minds and resources into a bright new future in bio-based composites. This requires vision, risk, capital and commitment. The future is in our hands.
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