Sustainable composites from natural resources

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Abstract

In order to insure a continuous supply of natural agricultural 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 agricultural-based composites utilizing the natural resources, considerations of multi-land use, and the protection, restoration, and conservation of the total ecosystem.

Agricultural 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. Plant fibers have a high aspect ratio, high strength to weight ratio, and have good insulation properties (sound, electrical, and thermal). The fiber structure is hollow, laminated, with molecular layers and an integrated matrix.

It is possible to make complex shaped composites directly using fiber mat technologies. Successful application of this technology depends on the development of a fiber mat which will maintain its physical integrity until it is used to form a final product. Fiber mats can be made by physical entanglement (carding), nonwoven needling, or thermoplastic fiber melt matrix technologies.

1 Introduction

Agricultural 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.

As we start 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.

We traditionally think of agricultural composites as solid, i.e. wood. As the availability of large diameter trees decreased (and the price increased) the wood industry looked to replace large timber 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, defects such as knots, cracks, checks, etc are eliminated and the furnish is more uniform and consistent. Also, as the element size becomes smaller, the composite becomes more like a true material, i.e. consistent, uniform, continuous, predictable, and reproducible. For many new agricultural composite products, the use of fibers will become more common and these fibers can come from many different types of agricultural sources.

The traditional source of agricultural 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.

2 Past, present, and future trends

If the definition of a composite is any mixture of agricultural 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. 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.

There are several trends today that can help us look into the future of sustainable agricultural composites. These include: competition of resources, inventory, resource selection, and sustainability, recyclability and environmental issues, durability and performance, life cycle assessment, products and production, and quality assurance and testing.

2.1 Competition of resources

Global agricultural 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 agricultural 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. We also recognize that much of our clean, water comes from our forest lands.

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. Agricultural 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,

2.2 Inventory, resource selection and sustainability

Table 1 shows the inventory of some of the major sources of agricultural 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. By using a harvest index, it is possible to determine the quantity of residue associated with a given production of a crop.

While the data presented in Table 1 is important and interesting, it is not very useful. The data that would be useful for commercial use is the inventory of agricultural 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.

Table 1 - Inventory of major potential world fiber sources

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

In considering a given agricultural resource for composites, fiber chemistry and properties are a major consideration. Table 2 shows the fiber dimensions and chemical composition of several different types of plant. 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.

Table 2. Dimensions and chemical composition of some common agro-fibers[1]

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

[1]Listed by increasing mean fiber length

2.3 Recyclability and environmental issues

Using environmentally sound technologies to make agricultural 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. 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.

From the environmental stand point, one of the big issues in agricultural 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.

2.4 Durability and performance

Agricultural 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.

Properties such as dimensional instability, flammability, biodegradability, and degradation caused by acids, bases, and ultraviolet radiation are all a result of chemical degradation reactions (hydrolysis, oxidation, dehydration, and reduction) which can be prevented or, at least, slowed down if the cell wall chemistry is altered. This approach is based on the premise that the properties of any resource are a result of the chemistry of the components of that resource. In the case of ago-based resources, cell wall polymers, extractives, and inorganics are the components that, if modified, would change the properties of the resource. Based on performance requirements, modifications can be carried out to change what needs to be changed to get the desired change in property and, therefore, change in performance.

One of the most studied chemistries to improve performance properties of agricultural-based composites involve reactions with acetic anhydride (acetylation). Chemical modifications of this type react with accessible hydroxyl groups on the cell wall polymers. These are the same hydroxyl group involved in the natural degradation Chemistries. The addition of a simple acetate group on the natural fiber changes both rate and equilibrium properties. Table 3 shows a summary of some of the properties changed through this simple

Table 3 - Equilibrium moisture content (EMC), thickness swelling (TS), biological resistance modulus of rupture (MOR), modulus of elasticity (MOE), and tensile strength (TnS) parallel to the board surface of fiberboards made from control and acetylated pine fiber (8% phenolic resin).

Weight Percent Gain %	EMC and TS 90% RH , 27C EMC %	TS %	Weight Loss After 12 Weeks Brown-rot Fungus %	White-rot Fungus %	MOR MPa	MOE GPa	TnS MPa
0	19.7	29.2	68	7	37.1	3.7	19.0
19.6	8.2	2.7	<2	<2	32.9	3.3	15.6

chemistry. Moisture sorption is greatly reduced as evidenced by a reduced equilibrium moisture content in the cell wall. Cell wall swelling has been reduced by a factor of 10 and. attack by both brown- and white-rot fungi has been eliminated. Mechanical properties have been somewhat reduced but not significantly. Many other chemistries have beer, used with similar results.

2.5 Life cycle assessment

The agricultural-based composite 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. 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

2.6 Products and production

There are many opportunities to expand existing markets and develop new markets for agricultural composites. One past trend that exists in the agricultural composite industry is that when a new product is developed, its intended market is, in many cases, to replace an existing agricultural composite. We have what might be called a agricultural composite pie. We expand the market of one agricultural composite at the expense of another agricultural 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 agricultural composite pie, it only changes the size of each piece within the pie. We need to expand the whole pie!

To insure the most cost effective approach to the utilization of an agricultural resource, each part of a given agricultural 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,

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.

2.6.1 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 agricultural 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.

2.6.2 Filters and sorbents

Medium and high density fiber mats or fiberfiller containers can be used for air and water filters. The density of the mats can be varied, depending on the size and quantity of material being filtered and the volume of air or water 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 filtering aids to take particulates out of waste and drinking water or solvents. Fiters can also be used to remove heavy metals, pesticides, organics, oil and grease, nitrogen, phosphorus, and other contaminates from water.

2.6.3 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 agricultural composites which have lower performance requirements. Within the agricultural composites, performance varies from multi-layered plywood and laminated lumber to low cost particleboard. Structural agricultural composites, intended for indoor use, are usually made with a low cost adhesive which is not stable to moisture while e;.tenor grade composites use a thermosetting resin that is higher in cost but stable to moisture.

2.6.4 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 agricultural composites, they lend themselves to products that "surround" people like wall coverings, room dividers, and furniture.

2.6.5 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 the 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 foxmation 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.

2.6.6 Packaging

Medium and high density agricultural 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. Agricultural 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 agricultural pallet.

2.6.7 Combinations with Other Resources

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 perfomance as well) but to the agricultural industry, this represents an increased value for the agricultural component.

Blending of the plastics with the agricultural fibers may require compatibilization to improve dispersion, flow and mechanical properties of the composite. Extrusion of agricultural filled plastics for the automotive industry is well known and has been used for more than twenty years. Typical blending involves the plastic-fillerheinforcement 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 agricultural 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.

2.7 Quality assurance and testing

There is a need to develop an assurance of quality in the use of agricultural products in worth markets especially where they are replacing traditional products made from other resources. This requires the need to develop codes and specification of each desired agricultural 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 agricultural composite material.

3 Conclusions

The future of sustainable, value added, agricultural composites will be very exciting and dynamic. By considering the entire agricultural resource as a raw material for agricultural composites, we are not limited to just one type of agricultural resource. The 21st century may well be known as the cellulosic era. There will be more products that are derived from agricultural resources. This expanded role for agricultural resources will not only take place in composites, but also in chemicals, pulp and paper products, fuels, lubricants, bioenergy, and many other products.

High Performance Structures and Composites

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