INTERNATIONAL WHEAT QUALITY CONFERENCE
Session VII. Advancements in Processing Technology

Novel Uses of Wheat By-products

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ABSTRACT

Wheat straw is renewable, widely distributed, available locally, moldable, anisotropic, hydroscopic, recyclable, versatile, non-abrasive, porous, viscoelastic, easily available in many forms, biodegradable, combustible, compostible, and reactive. It also has a high aspect ratio, high strength-to-weight ratio, and has good insulation properties (sound, electrical, and thermal). The fiber structure is hollow and 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.

Many possible composite products can be made using wheat fibers including structural (using thermosetting resins) and nonstructural (using either a thermosetting or thermoplastic resin) materials, geotextiles and molded products (using fiber mats prepared by physical entanglement, nonwoven needling, or thermoplastic fiber-melt matrix technologies), sorbents and filters (for removing pollutants from contaminated air, water, and/or soil), packaging, and in products in combination of other resources. Success or failure in producing these products depends on many factors including codes and standards, economies of scale, availability of resources, energy and labor costs, resource handing, collecting and shipping, and overcoming historical biases.

Wheat fibers can be combined with other resources such as plastics, glass, metals, and synthetics. The objective is 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. The properties of wheat fibers can also be modified through physical and chemical technologies to improve performance of the final composite.

SPEAKER PAPER

Introduction

Using the term "novel" in the title could indicate that this paper will deal with any use of wheat by-products that are at present not being produced. The authors, however, will temper the term "novel" with some measure of economic viability and only discuss opportunities that might be novel but also economically feasible. We ask readers to be creative in their approach to this subject and think "outside the box." We will include some possibilities that do not yet have enough technical and/or economic data to make a qualified decision on their possible commercial future. We will mainly deal with applications of wheat straw for a variety of composite applications.

By-products from growing wheat have been used for many years for a variety of applications. The use, for example, of wheat straw as structural filler for mud bricks dates back several hundred years, for pulp back to 1827, and for building panels back into the early 1900's. So, the idea of using residues from wheat harvesting is not new.

In the United States, we are still planting more trees than we are harvesting, thus in a sense, there is no real economic need to use wheat straw as a source of fiber. A segment of society, however, is concerned about cutting down trees and is willing to explore alternative sources of fiber to be used for paper and composites. While a portion of the straw must stay on the land to retain soil structure and to prevent erosion, a large portion can be, and is, removed and utilized. The sheer volume of unused straw fiber is too great to ignore. Diversifying the agricultural economy, saving the "family farm," turning "straw-into-gold," conserving trees — these are concepts that appeal to people on many levels.

Because straw is a by-product of another process obtainable in mass on level terrain, it is relatively inexpensive, if it doesn't have to be shipped too far. Delivered costs of field-dried straw run about $35/ton compared to $50/ton (dried basis) for wood. A further advantage is the lower drying burden, since ripened stalks dry down to about 12% moisture content in the field. But, the economics of utilization are hampered by several technical and logistical issues that must be addressed before wheat straw will be considered for a wider variety of applications. First is the seasonality of the crop. Almost all of the inventory will be available over a very short, approximately three-month period. This means that storage without loss of mass or properties becomes a major issue. Separation and cleaning then follow and since the straw is so light, some form of densification will be needed to enable economic transport. It may be possible to make pellets from wheat straw that can be shipped to a central location for processing into products, but it is probably not reasonable to consider shipping wheat straw more than about 20 miles.

Inventory and Properties

It is estimated that approximately equal amounts of grain and stalk are produced during the growing season. Estimates vary, but most quote between 1.3 and 1.0 tons of wheat straw generated for each tonne of grain produced. Table I shows the estimated quantity of several different types of

Table I. Inventory of U.S. Straw

Fiber Source	**Potential Quantity (dry tons)**			
	ILSR [1]	Atchison [2]	USDA, Ag Stat [3]	FAO [4]
Straw				
Wheat	112,700,000	76,000,000	78,900,000	62,662,000
Barley	20,800,000	7,000,000	12,000,000	6,136,000
Sorghum	13,500,000	28,000,000	33,700,000	
Oat	10,700,000	5,000,000	6,000,000	2,122,000
Rice	7,400,000	3,000,000	7,500,000	
Cotton	5,100,000	4,600,000	7,100,000	
Flax(seed)	4,500,000	500,000	700,000	
Rye	1,500,000	400,000	400,000	
Grass(seed)	1,200,000	1,100,000	900,000	

[1] Institute for Local Self-Reliance (1997).

[2] Atchison (1994).

[3] USDA, Agricultural Statistics (1993) and USDA, Economic Research Service (1997).

[4] FAO (2000).

straws. It is interesting how different the estimates are, depending on the source. The largest amount of straw is estimated to be available from the harvesting of wheat. Most likely, different types of straw will be mixed and not utilized separately unless some unique property is found from one straw as opposed to another.

Table II shows chemical content and fiber dimensions of several common straws as compared to both hardwoods and softwoods. In general, the straws have less cellulose and lignin than wood, but do contain enough cellulose that they have been considered as a source of pulp and paper.

The ash content of straws varies, but tends to be higher than in wood. The nodes and chaff contain particularly high amounts of ash, and it is desirable to remove as much of these as possible.

Table II. Dimensions and Chemical Composition of Some Common Straw Fibers

Type of Fiber	Cellulose (%)	Lignin (%)	Fiber Dimension (mm) Mean Length	Mean Width
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
Coniferous wood	40-45	26-34	4.1	0.025
Deciduous wood	38-49	23-30	1.2	0.03

Composite Products

We would like to consider using wheat by-products, mainly stalks, for the following products; (1) geotextiles, (2) filters, (3) sorbents, (4) structural composites, (5) non-structural composites, (6) molded products, (7) packaging, and (8) combinations with other materials. There is some overlap among these areas. For example, once a fiber web has been made, it can be directly applied as a geotextile, filter, or sorbent, or can be further processed into a structural or non-structural composite, molded product, used in packaging, or combined with other resources.

Wheat straw can be reduced to fiber by several means. The one most often used is a simple, hammer-milling process that reduces the straw to fiber bundles by mechanical action. This usually results in a high percentage of very small particles. It can also be refined using single- or double-disk refiners in a wet process. Wax content and high inorganic content can cause problems in all types of processing.

(1) Geotextiles - Geotextiles derive their name from the two words geo and textile and, therefore, mean the use of fabrics in association with the earth. Wheat straw can be combined with a long fiber such as cotton, jute, flax, or kenaf to form flexible fiber mats. These can be made by physical entanglement, nonwoven needling, or thermoplastic fiber-melt matrix technologies. The two most common types are carded and needle-punched mats. 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. Typical compositions of these mats would allow up to 90 percent wheat straw. The melt matrix mats are made using a low-temperature melting thermoplastic fiber that is heated during the processing to stick the mats together through thermobonding.

Geotextiles, both low to high densities, have a wide variety of applications. They 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 home sites 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 topsoil.

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 them.

(2) Filters - Medium- and high-density fiber mats can be used for water and air filters. Density of the mats can be varied, depending on the size and quantity of material being filtered and the volume of water or 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. These mats can also be used as filtering aids to take particulates out of waste and drinking water or solvents.

(3) Sorbents - Tests are presently underway to use a wide variety of agro-based sorbents to remove heavy metals, nonmetals, pesticides, and oil from rainwater runoff in several cities in the United States. Medium- and high-density mats can also be used for oil-spill cleanup pillows. Other potential sorbent applications include removal of dyes and trace chemicals in solvents and purification of solvents. Straw fibers can be chemically modified or surface-functionalized to become more reactive and specific in removing targeted contaminates from water.

(4) Structural Composites - A structural composite is defined as one that is required to carry a load in use. In the housing industry, for example, these represent load-bearing walls, roof systems, sub-flooring, stairs, framing components, furniture, etc. In all cases, performance requirements of these composites are spelled out in codes and/or in specifications set forth by local or national organizations.

Some characteristics of straw pose peculiar processing problems. One of them is its tubular morphology. If not split open, resin coverage on the interior will be nonexistent, causing weak internal bond and swelling properties.

Because of its waxy coating, straw, if used in its particle form, does not present an easy surface for adhesives such as urea (UF) or phenol formaldehyde (PF) to bond to. However, it can and are being used with PF resins in fiberized form (see Table III). A diisocyanate-based adhesive works well with particles (Troger and Pinke 1988), but costs about two and four times as much as PF and UF, respectively.

Table III shows mechanical properties of fiberboards made using wheat straw as compared to fiberboards made using both a softwood and a hardwood fiber. The wheat straw board has a much lower modulus of rupture as compared to a pine fiberboard but is comparable to the fiberboard made from beech fiber.

Table III. Properties of Fiberboards Made Using Wheat Straw (Average Board Density: 900 kg/m^3, 10% Phenolic Resin Content)

Type of Fiber	Bending Strength (MOR) [MPa]	Modulus of Elasticity (MOE) [GPa]	Internal Bond Strength (IBS) [MPa]	Thickness Swelling (TS) %
Wheat Straw	34	2.1	2.0	25.1
Pine	53	3.7	2.3	21.3
Beech	38	3.1	1.8	17.0

Wheat straw has been used to make structural panels (Fujimoto et al 1988, Donnell 1995, Douglas 2000, Bowyer and Stockmann 2001). Several plants have been built in the United States and Canada to produce strawboards, but some have had a hard time maintaining production. These difficulties have been ascribed to mistakes in scaling the plants below modem economic standards and a focus on using straw in particle rather than fiber form.

(5) Non-Structural Composites – As the name implies, non-structural composites are not intended to carry a load in use. These can be made from wheat straw combined with an adhesive to make a variety of products as demonstrated in laboratory trials for acoustical tiles (Wisniak and Lauterback 1962), insulation board (Lathrop and Naffziger 1949, Srivastava and Gupta 1990), and furniture cores (Russell 1990). Non-structural composites are generally lower in cost than structural composites and have fewer codes and specifications associated with them.

(6) 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 wood-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 primary board producer can realize secondary-manufacturing profits. Instead of making low-cost flat-sheet type composites, it is possible to make complex-shaped composites directly using the mat technologies described earlier.

In this technology, fiber mats are made by including an adhesive that 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 pressing, using the desired shaped mold in the press. 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.

(7) Packaging - Wheat straw can be used to make corrugated sheets (Nakai et al 1976), shipping containers (Lathrop et al 1951), or can be shaped to "nest" the product using either the molding technology described previously or using pulp-molding technology.

Wheat straw can also be added as a reinforcing fiber in starch foam "clam shell-type'' food containers or food trays. The surface of these products can be coated with wax or plastic, or made hydrophobic using cold plasma technologies.

(8) Combinations with Other Resources - It is possible to make completely new types of composites by combining different resources. For example, wheat flour or straw fiber may be combined 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.

Wheat straw fiber/glass fiber composites can be made using glass as a surface coating. Composites of this type can have a very high stiffness-to-weight ratio. The fiber mats described earlier can be used in resin-injection molding (RIM) or used to replace, or in combination with, glass fiber in resin-transfer molding (RTM) technologies.

Metal films can be laminated onto smooth, dimensionally stabilized straw-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 agro-based resources have lost market share.

Straw flour can also be combined in an inorganic matrix (Ludwig 1950). Such composites are dimensionally and thermally stable, and they can be used as substitutes for asbestos composites. Inorganic, bonded wheat-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 comes from combining natural fibers with thermoplastics (Cheng and Li 1988, Johnson et al 1997). Since prices for plastics have risen sharply over the past few years, adding a natural powder or fiber to them provides a cost reduction to the plastic industry (and in some cases increases performance as well). But to the wheat-based industry, this represents an increased value for wheat by-products. Most of the research has concentrated on using a compatibilizer to make the hydrophobe (plastic) mix better with the hydrophil (wheat). The two components remain as separate phases, but if delamination and/or void formation can be avoided, properties can be improved over those of either separate phase. These types of materials are usually referred to as natural fiber/thennoplastic blends. Addition of wheat straw to polypropylene, using a 2% maleic anhydride-grafted polypropylene (MAPP) by weight as a compatibilizer, increased tensile strength by about 15 % and flexural strength by about 40%, as compared to virgin polypropylene (Johnson et al 1997).

Conclusions

One of the key barriers in developing new products from wheat straw is the high cost of developing new markets. In most cases, new products are being developed by small companies that are under-capitalized and lack the needed resources critical to moving beyond the research stage.

There are some success stories in the utilization of wheat straw in making composites. Blending the straw with polypropylene to produce injection-moldable products is a commercial success, although a small one now. The strawboard industry is in its early stages of development and growing pains are evident. Process problems, financial difficulties, and even failure have been experienced across the industry. At its present state, it does not appear to have a significant cost advantage over established products and its growth is greater on paper than in reality. Taking active operations at their nameplate capacities, they represent only about three percent of Canadian/U.S. particleboard/MDF capacity. For major building material distributors coming under environmental pressures, such products could become attractive even without economic benefits.

If further research solves some of the problems identified in this paper and adds a cost advantage, a progression in the composite industry toward agricultural residues could ensue.

In the future, smart people will invest in new products from wheat by-products. Wise people will know which ones those are.

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O. K. Chung and J. L. Steele, Editors

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Grain Industry Alliance   Manhattan, Kansas, USA   August 2003

Rowell, Roger M., Spelter, Henery. 2003. Novel uses for wheat by-products. In: Proceedings of the international wheat quality conference; 2001 May 20-24; Manhattan, KS. Manhattan, KS: Grain Industry Alliance. 417-423