Biobased Structural Composite Materials for Housing and Infrastructure Applications: Opportunities and Challenges

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Abstract

Biobased structural composite materials for use in housing and infrastructure applications are new, emerging materials that can play a significant role in the next generation of American housing applications. Efforts are underway to solve the research issues necessary to combine fibers from non-woody plants with plastics made from plant materials into structural composite materials. These developments are taking place at a critical time when political, economic and international conditions are aligned to provide the 'technological pull' to support this effort. Increasing domestic and global population is requiring more and better housing. Pressure is building to preserve trees for ecological and climatic conditions. Development of sustainable materials as alternatives to petroleum based materials are being sought to decrease the dependence on imported oil, to reduce carbon dioxide emissions and to generate more economic opportunity for the agricultural sector both in the US and globally. US government policies have been changed to provide preferential procurement status for biobased materials. The availability of biobased structural composites offer the opportunity for environmental gains, reduced energy consumption, lighter weight, insulation and sound absorption properties, reduction in volatile organic emissions, and reduction in the dependence on petroleum based and forest product based materials. Several critical issues remain to be solved to achieve the objective of producing an affordable, alternative construction material for the housing industry of the 21st century. They include research into the methodology for optimal selection, surface treatment and combinations of natural fibers, process methods for optimal combination of natural fibers with suitable biobased plastics, moisture and thermal durability and stability enhancement, economically viable manufacturing processes to maximize natural fiber composite properties and new design methodologies involving hybridization at both the constituent and structural levels.

Keywords: Housing materials, construction materials, biocomposites, structural composites, sustainable materials

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Introduction

Contemporary housing needs are challenging designers and builders to utilize more inventive materials in order to provide housing that is environmentally benign and at the same time provides for the requisite occupant environment and operating efficiency. Increasing attention is turning to bio-based materials from renewable resources. The future for bio-based building materials is bright (Figure 1) (Mohanty, 2000) and several new agricultural natural fiber-based building materials are already making their mark in the building industry. Evidence is growing that natural fiber composites (bio-based composite materials) can be an economical commodity composite, which can be produced with useable structural properties at relatively low cost.

Themanufacture, use and replacement of conventional building materials (e.g. petroleum-based plastics, glass fibers, etc.) are becoming priorities because of the growing environmental consciousness. Executive Order 13101, *'Greening the Government Through Waste Prevention, Recycling and Federal Acquisition'*, established the setting of procurement priorities and preferences for materials that have significant amounts of biobased content, with the federal government acquisition percentages steadily increasing to the 50% level over the next several decades. The USDA under the *Farm Security and Rural Investment Act of 2002* is in the process of establishing guidelines for the level of biobased content required to meet the 'biobased' criterion with results expected shortly. Products attaining the proposed levels of biobased content would be able to carry the designation: "U.S.D.A. Certified Biobased Product."
Several categories identified for biobased designations and of importance to the Housing Industry are included in this regulation (Adhesives; Fibers, Paper and Packaging; Plastics; Paints and Coatings; and Construction Materials and Composites.) Some examples of the current language in the notice in the federal register are quoted below. (*Federal Register: December 19, 2003 (v. 68, No. 244, pages 70730-70746). "The Construction Material Subcategory includes product applications containing biobased adhesives, such as plywood and finger jointed lumber; oriented strand board, medium density fiberboard, and hardboard; engineered wood building components, e.g., laminated beams, trusses, finger jointed lumber, oriented strand lumber; moldings and trim; and decorative composites. Construction products include round wood; lumber; composites; and plastic-wood composite lumber and panels such as plywood, oriented strand board, medium density fiberboard, and hardboard that contains agricultural or wood-based materials.*

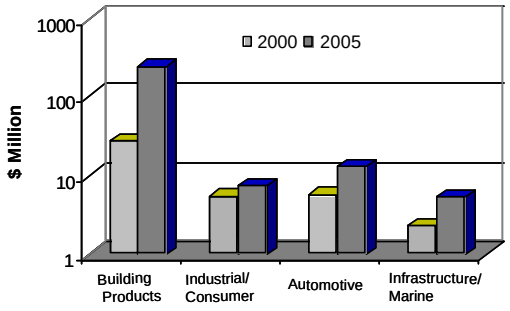

Figure 1: Growth Outlook For Biobased Composites by Application in US, 2000-2005

Table 1. Proposed USDA Biobased Content Levels	
Items	Minimum biobased content (%)
Adhesives	70
Adhesive Products	90
Construction material	85
Composite panels	70
Molded reinforced composites	10
Insulating foams and films	15
Components of mixed system products	20

The Composite Panels Subcategory is composed of nonstructural composite materials such as highly engineered blends of recycled paper products or agricultural wastes, biobased resins, and color additives which can combined to provide a composite and composite panels. Product applications include furniture, tabletops, trim, store fixtures, awards, plaques, trophies, indoors signs, and other interior or nonstructural uses. Composite panel products include panels made from straw or other agricultural residues. Molded Reinforced Composites Subcategory includes products, such as decorative trim, shingles, or siding, may be made from bioplastic resins used to bind inorganic fibers such as fiber glass or agricultural fibers such as kenaf. These resins may be made from a combination of biobased materials and may be reacted with petro-based chemicals to achieve functional properties."

Biobased content will vary with product classification. For example, *"Adhesive products are to have a minimum biobased content of 70 percent by weight of the adhesive. Finished products in which 90 percent of all of the adhesives used in production are biobased would be designated as biobased products."* The minimum biobased content proposed for some of the items in the Construction Material Category are tabulated in Table 1.

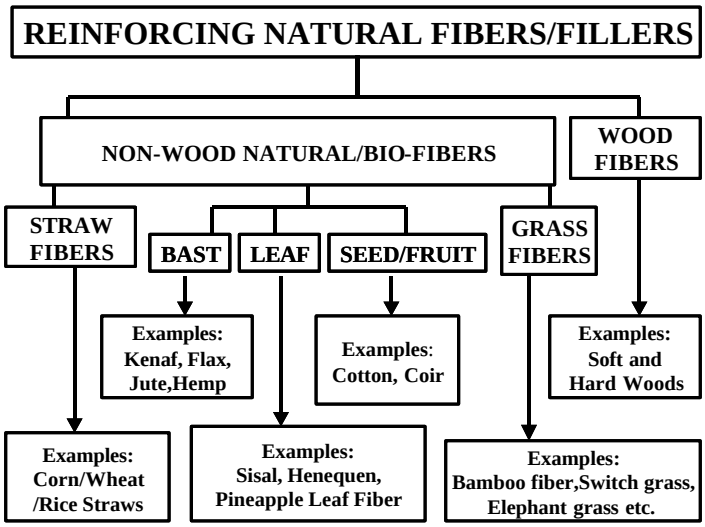

Figure 2: Natural/Bio-fibers for Biocomposites for the Housing Industry

Figure 3. Various Types and Sources for BioFibers.

In the structural materials area, there is a growing interest in the use of natural/bio-fibers as reinforcing components with petroleum and biobased thermoplastics and thermosets. Advantages of natural fibers over traditional reinforcing fibers such as glass and carbon are: low cost, low density, acceptable specific properties, ease of separation, enhanced energy recovery, CO_2 sequesterization and biodegradability. Thermoplastics have the added advantage of recyclability, but thermosets have the necessary mechanical properties for use as structural bio-composites. Bio-composites derived from natural fibers and petroleum-based thermoplastics or thermosets are not fully environmentally friendly because matrix resins are non-biodegradable but the biobased content of the final composite material falls within the definition of biobased materials. Even these bio-composites maintain a balance between economics and environment allowing them to be considered for applications in the automotive, building, furniture and packaging industries.

The use of reinforced thermoset composites is being led by automakers who have nearly doubled their use in the last decade, with expectations for growth of ~50% through 2004. In 2002, Reinforced Plastics demand was 3.7 billion pounds, with the construction industry accounting for ~32%; Reinforced plastics demand in the US is projected to grow 2.5 percent annually to over four billion pounds in 2007, valued at $6.5 billion.

Thermoset resins will remain dominant and account for 64% of all reinforced plastics demand in 2007. Reinforced polyester exhibits good weathering properties and heat and corrosion resistance, with good strength-to-weight ratios. It can be fabricated into a variety of rigid products, including boat hulls, storage tanks, shower enclosures, electrical components and pipes. Other reinforced thermosets include epoxy, phenolic, polyurethane and melamine. Reinforced thermoplastics will exhibit more rapid growth based on customer demands for higher performing and more aesthetic products. Polypropylene, thermoplastic polyester, nylon and

polycarbonate will present the best growth opportunities due to their suitability for a diverse range of applications.

Glass fibers will remain the leading reinforcement material due to their low cost and excellent performance. The use of natural fibers in FRP (fiber reinforced plastics) to replace glass fiber is starting to increase in a few applications. For example, the engine and transmission covers of *Mercedes-Benz* transit buses now contain polyester resin reinforced with natural fiber.

There is, however, a major drawback associated with the application of bio-fibers for reinforcements of organic matrix resins. Due to the presence of hydroxyl and other polar groups on the surface and throughout bio-fibers, moisture absorption can be high, which leads to poor wettability by the matrix resin and weak interfacial bonding between fibers and hydrophobic matrices. In order to develop composites with better mechanical properties, it is necessary to impart hydrophobicity to the biofibers by suitable chemical treatments (Mohanty, 2001).

The fiber mechanical behavior, its form (non-woven, woven, short/long fibers), the nature of the matrix, and fiber-matrix adhesion play vital role in controlling the properties of composites. This paper gives an overview of natural fiber reinforced polyester composites highlighting the future aspects of such bio-based composite materials in building applications.

REINFORCING NATURAL/BIOFIBERS

Plastics, whether petroleum or biobased, by themselves, are not fit for load bearing application due to their lack of strength, stiffness and dimensional stability. However fibers possess high strength and sufficient stiffness but cannot be used for load bearing applications because of their fibrous structure. In fiber-reinforced composites, the fibers serve as reinforcement held together by the plastic matrix into a material form with suitable strength and stiffness for structural applications.

Table 2: Modulus comparison of E-glass and some important Natural BioFibers

Fiber Type	Density (g/cm^3)	Elastic Modulus (GPa)	Specific modulus
E-glass	2.55	73	29
Hemp	1.48	70	47
Flax	1.4	60-80	43-57
Jute	1.46	10-30	7-21
Sisal	1.33	38	29
Coir	1.25	6	5
Cotton	1.51	12	8

Bio-fibers may be classified in two broad categories: Non-wood fibers and Wood fibers (Figure 2). Interest in the use of non-wood cellulose fibers in plastic composite structures has increased rather dramatically in recent years. The best-known examples are: (i) bast fibers: flax, ramie, kenaf/mesta, hemp and jute (ii) Leaf fibers: sisal, pineapple leaf fiber (PALF), and henequen (iii) seed fibers: cotton; fruit fibers: coconut fiber, i.e. coir (Figure 3). All natural fibers (wood and non-wood) are lingo-cellulosic in nature with the basic components being cellulose and lignin. The density (g/cm^3) of natural fibers (varies from ~1.2-1.5) which is much less than that of E-glass fiber (2.55). The specific strength and specific modulus[7] of natural fibers are comparable or even superior to E-glass fibers (Table 2). Non-wood bast (from the stem part of the plant) fibers are poised to be utilized to a greater extent than wood fibers in bio-composite housing structures.

MATRIX POLYMERS FOR BIO-COMPOSITES

Polyester resins, because of their versatility and low cost, are widely used in polymer composites that have utility in the housing industry. Polyester resins are classified as: (i) ortho resins, (ii) isoresins, (iii) bisphenol-A-fumarates, (iv) chlorendics, and (v) vinyl ester. Ortho-resins, known as general-purpose polyester resin, are based on phthalic anhydride, maleic anhydride and glycols. Ortho-resin is the least expensive among all polyester resins. The solutions of unsaturated polyesters and styrene vinyl monomers (reactive diluents) are known as unsaturated polyester (UP) resins. Considerable work has been reported on the synthesis, characterization, and curing behavior of UP resins[8]. The curing reaction of UP is a free-radical chain growth polymerization between reactive diluents styrene and UP resin with considerable versatility for curing at room or elevated temperature by varying the catalyst package.

The choice of biobased polymers for use in composites is small but growing (Table 3). On the thermoset side, polyols made from plant oils can be formulated with curative and organic reactions to make crosslinkable thermoset matrices. Soy bean oil is the largest potential source that has been demonstrated as being convertible to polyols, but other oils, such as cashew nut oil can be used with equal success. These biobased materials can be used by themselves or in combination with petroleum based chemicals to produce thermoset matrices.

In a recent NSF-PATH sponsored research at Michigan State University (Drzal, 2001), natural fiber composites (biocomposites) were made using a non-woven fiber mats (90% hemp fiber with 10% thermoplastic polyester binder) as reinforcement and unsaturated polyester (UPE) resin. Blends of UPE and functionalized vegetable oils as the polymer matrix at 30% volume fraction of fiber were also used. It was found that the thermo-mechanical properties of these composites were superior to petroleum-based systems. The notched Izod impact strength of bio-composites from biobased resin blends of UPE and functionalized vegetable oil and industrial hemp fiber mats were enhanced by 90% compared pure UPE-industrial hemp fiber mat composites. Tests also showed improvement in the tensile properties of the composite as a result of the incorporation of the derivitized vegetable oil.

On the thermoplastic side, there are also a few polymers that are potential candidates for use in biocomposites. Cellulose plastic has been a commercial product for many years and with proper toughening is a 100% biobased matrix that is commercially available. Starch based polymers are

available but their utility will depend on the ability to reduce their moisture absorption. Poly (lactic acid) PLA, is also already a commercial product with properties similar to polystyrene. Another class of biopolymers, poly(hydroxy alkanoates) have properties similar to polyesters and are on their way to commercialization. Final use of these biobased polymers depends on the ability to achieve modifications that allow easier processing and enhanced toughness in the final biocomposite.

Table 3. Biobased Polymers, Plastics and Manufacturers

Biobased Thermoplastic From Renewable Resources	
Polymer	*Manufacturer*
Cellulose Plastic	Eastman Chemical
Starch Plastic	National Starch, Novamont
Poly Lactic Acid	Cargill-Dow, Mitsui, Toyota
Poly Hydroxy Alkanoate	Metabolix
Biobased Thermoset Plastic From Renewable + Petroleum Resources	
	(multiple)
Biobased polyurethane (from vegetable oil based polyol and fossil fuel derived isocyanates)	Still under developmental state
Biobased epoxy (from combination/blend of epoxidized vegetable oil and fossil fuel derived epoxy)	*(multiple)* Under research and developmental stage and yet to be commercialized
–Sorona (condensation of 1,3 propane diol from corn with fossil fuel derived terephthalic acid)	DuPont

Current State of the Art

Natural fibers combined with synthetic fibers (e.g. glass) in a totally biobased polymer matrix or a hybrid blend of biobased and petroleum based polymer matrix have the potential to dramatically change the nature of structural materials and emerge as realistic alternatives to glass-reinforced petroleum based composites. They can deliver the same performance for lower weight and they can also be 25-30 percent stronger for the same weight. Research success from laboratory scale experiments (Belcher, 2001)(Mehta, 2003) has shown that it is possible to produce bio-composites with properties that can compete with glass fiber reinforced composites. Natural fiber (NF) unsaturated polyester (UP) composites show lower density, equal flexural modulus, comparable flexural strength but relatively poorer impact strength as compared to a glass fiber (GF) composites (Schlosser, 2000). This progress has been achieved because of utilization of an integrated research approach incorporating three important factors:

- Low cost but effective bio-fiber surface treatment
- Matrix modification incorporating functionalized vegetable oil
- New, property-enhancing bio-composite processing
- Hybrid structural biocomposite plates and beams

Bio-fiber treatments and Design of "Engineered Natural/Bio-fibers"

"Engineered Natural/Bio-fibers" are defined as a blend of surface treated bast (e.g. Kenaf, Hemp) and leaf fibers (e.g. Pineapple leaf fiber, PALF) whose composition is based on the fact that the correct blend achieves an optimum balance in mechanical properties. Kenaf and/or Hemp based composites exhibit excellent tensile and flexural properties, while leaf fiber (PALF) composites give the best impact properties to composites. A blended composition of two bast and one leaf fiber can thus achieve a balance of flexural and impact properties of the targeted bio-composites. Natural fibers could be surface treated to achieve good matrix adhesion utilizing any of four surface treatments (alkali treatment, methacryloxypropyl trimethoxy silane treatment, acrylonitrile treatment, and unsaturated polyester resin–MEKP treatment.) Alkali treatment (AT) of natural fibers appears to be very promising, having the right combination of surface chemical and structural benefits along with low cost. The alkali treatment enhances the biofiber surface roughness, causes surface fibrillation and thus drastically improves fiber-matrix adhesion. Acrylonitrile treated hemp-unsaturated polyester resin bio-composites have achieved the highest mechanical and thermal properties.

Matrix modification (Blend of polyester resin and derivitized vegetable oil)

Unsaturated polyester resin is, at the current time, the matrix resin used in the largest quantity; but it is petroleum-based and is not eco-friendly. A new bio-resin, compatible with unsaturated polyester resin was developed from soybean oil phosphate ester polyol. The matrix formulation was altered by addition of new bio-resin, in various amounts, thus lowering the content of petroleum products in the system. Curing behavior can be altered to provide full cure at low temperature. Toughness of the matrix resin can be increased with addition of the bio-resin. Hybrid composites consisting of glass fibers, surface treated natural fibers and biobased blended polyester resin were made, with almost the same mechanical and thermal properties as all glass-polyester composites.

Bio-Composite Processing

Bio-composites can compete with glass-polyester composites both on cost and performance basis. Most of the existing results on bio-composites are based on hand-lay-up laboratory-scale fabrication techniques. However the success of a high volume processing technique will be necessary to economically produce bio-composites for housing paneling applications. A unique new process for fabrication of bio-composites was recently created under the above-mentioned NSF-PATH project. This process is similar to the Sheet Molding Compound (SMC) process but is a new and necessary approach for bio-composites. Biofibers suitable for reinforcement are discontinuous in length and are chopped to short lengths to incorporate them into polymer matrices. Conventional extrusion processes damage the fibers and lower their properties. Therefore, new processes have to be developed, or older ones modified, in order to produce structural biocomposites with well preserved properties. One such process is the sheet molding process (SMC) where chopped fibers are combined with a thermoset resin and a filler (calcium carbonate) to produce a compression moldable material suitable for low cost housing panels. A schematic representation of a continuous SMC bio-composite process is shown in Figure 4. The

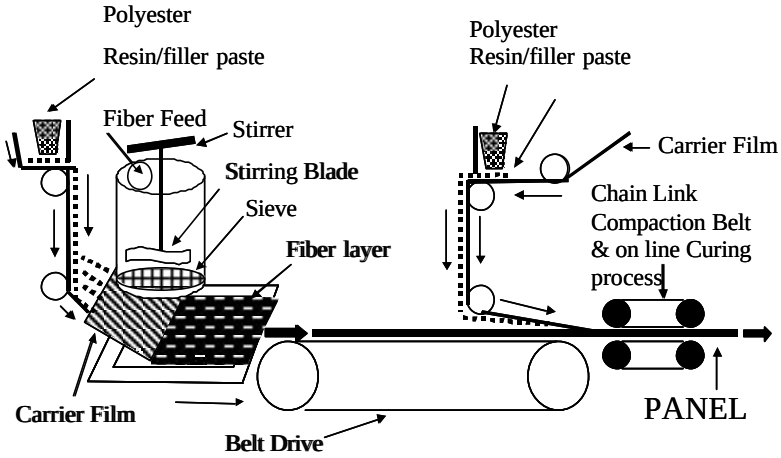

Figure 4. Schematic of Continuous Bio-Composite Sheet Molding Compound Panel (BCSMCP) Manufacturing Process at Michigan State University

short production cycle times and the excellent surface appearance make SMC attractive as a panel material. SMC properties can be tailored by varying the fiber content.

Hybrid Biocomposite Structural Forms

The concept of hybrid systems for improved material or structural performance is a well-known concept in engineering design. Nature's own material and structural designs show how high structural performance can be achieved with non-exotic constituents through hybrid combinations assembled in optimized hybrid hierarchical configurations (Gunderson, 1993) (Nogata, 1997). Recent work has shown that the properties of hybrid natural/glass composites with only ~6 wt.% glass fiber loading have been found to be an effective way to improve mechanical properties and dimensional stability (moisture, temperature, etc.) of the composite (Mishra, 2003).

Among nature's most common and efficient structures are cellular sandwich structures, which consist of a complex network of different-sized cells arranged across the section leading to dense regions (i.e. skins) integrally, connected to regions of lower density, or core (Wainwright, 1982). The stiffness of biocomposites can thus be overcome by structural configurations that place material in specific locations for highest structural performance. Cellular materials have the general form of either two-dimensional (honeycombs) or three-dimensional (foams) cell arrangements with unique properties that depend on the solid material composition, the volume fraction of the solid, and the arrangement and geometry of the cells (Gibson, 1988).

Integration of the above concepts of materials hybridization with optimized hierarchical cellular structural forms have been shown to improve the performance of biocomposite materials for load-bearing structures allowing them to effectively compete with glass fiber composites (Burgueño,2003a, 2003b) (Quagliata, 2003). Cellular biocomposite cores made from industrial

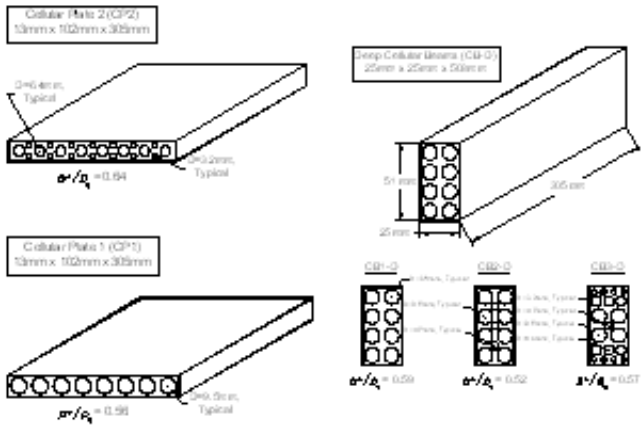

Figure 5. Cross-section geometry of biocomposite hierarchal cellular plates and beams

hemp or flax fibers with unsaturated polyester and hybridized with woven jute, chopped glass and unidirectional carbon fabrics showed improved stiffness, strength and moisture-absorption stability, while flexural tests on laboratory-scale beams and plates (Figure 5) demonstrated enhanced structural behavior. The mechanical properties are enhanced by efficient material arrangement and contribution of the stiffer and stronger synthetic fibers, whereas the reduction in moisture absorption behavior is due to the barrier provided by the more impermeable synthetic fibers. Micromechanics and sandwich analyses adequately captured material and structural response and the benefit from residual stresses was evaluated. Results from this study indicated that cellular biocomposite beams and plates not only have the potential to serve as primary load bearing components, but that with additional research they can compete with conventional structural materials.

Future Research Directions

New environmental regulations and changing governmental attitudes emphasizing biobased materials have stimulated the search for new products and processes that are compatible with the environment. American market studies clearly identify the potential impact and opportunities for natural fiber biobased structural composites. Natural fiber composites have the potential for major applications in building products. For biocomposite structural components to become a reality in load-bearing applications, additional research is required.

Areas requiring attention are those that address the current limitations of biocomposites in structural applications. They include a lack of uniformity in biofiber properties; biofiber instability in storage; cost-effective surface treatments for biofibers; biocomposite thermal, moisture and fungal environmental sensitivity; composite fabrication processes which degrade biofiber morphology and properties; low biocomposite stiffness and impact resistance; and uncontrolled biocomposite biodegradability. This gives rise to the following research needs:

Biofober Properties: Biofiber strength and stiffness needs to be improved. Laboratory measurements on pristine fibers indicate that properties equal or better than glass fiber are attainable. An important approach may be new chemical and/or enzymatic retting to prepare biofibers for storage and use. Biofober surfaces are hydrophilic, which makes them easy to adhere to but susceptible to moisture attack. New cost-effective surface treatments are required to make biofiber surfaces more hydrophobic without reducing adhesion to the polymer matrix.

Biocomposite Matrices: Research is required into approaches to make thermoset and thermoplastic biobased matrices stable during their expected structural lifetime but able to be 'triggered' into biodegradability in a controlled manner. Research is required into strategies to allow easier processing of thermoplastic matrices at lower temperatures. Since ~200°C is the upper limit for biofiber stability, processing will be limited to this temperature. Nano fillers and additives that can be added to thermoplastic matrices to reduce moisture absorption and flammability without increasing viscosity or introducing environmentally 'unfriendly' chemicals need to be identified.

Biocomposite Fabrication Processes: Research is required to identify and develop practical biocomposite fabrication processes that can increase fiber content, increase fiber alignment, and reduce biofiber degradation and attrition.

Micro and Macro Mechanical Models: Biocomposite mechanical properties that are of prime importance for structural applications include stiffness, impact resistance and resistance to creep. Both material modification approaches and unique structural design approaches will be required to produce competitive structural materials. Biofibers inherently have a higher degree of variability compared to synthetic fibers. Micro and macro mechanical models will be required for performing parametric and optimization studies in the design of hybrid designs that not only maximize structural performance but also reduce the effect of biofiber property variability.

Overall the potential for biocomposites to have a positive impact on materials for the housing industry is great. Composite materials based on renewable resources can lead to viable low-cost structural components and viable alternatives to conventional structural materials for current and future structural applications. The availability of low-cost structural components based on renewable resources will be a great asset for current and future structural applications.

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