Natural Fiber Reinforced Polymer Composite Materials for Wind Turbine Blade Applications

[1]Mr. Ganesh R Kalagi, [2]Dr. Rajashekar Patil, [3]Mr. Narayan Nayak

Department of Mechanical Engineering
SMVITM Bantakal Udupi, India 574115

***Abstract*: Wind turbine is a device that converts kinetic energy from the wind into electrical power. Among all the parts of wind turbine such as blades, hub, gear box, nacelle, and tower; nacelle and wind turbine blades are generally made up of glass fibres and carbon fibres for better strength, low weight, and corrosion resistance. The main limitations of these materials are the availability, non-biodegradable, health hazardous and their fabrication cost, hence the aim of this research is to replace these materials with natural fibers. In this research work, application of natural fibres reinforced polymer composites in wind turbine, requirements to the composites, their properties, constituents, manufacturing technologies, and defects will be reviewed; promising future directions of their developments also will be discussed.**

***Keywords:* Natural fibres, Polymers, Multiaxial Reinforcement, Wind turbine blades.**

1. Background

A wide variety of sources including wood, coal, coke, oil, natural gas and nuclear materials have been used to generate energy. Over the years, the consumption of energy has increased due to the increasing population and civilization. At the same time, the ecological awareness has become the major environmental issue in the global marketplace. In today's scenario the major threat for the environment is the imbalance in the ecological system which is increasing due to the disposal of toxic waste. This issue has led to the increased interest on renewable and sustainable energy sources. The only concern for the sustainable development is minimum pollution and reduction in energy consumption [2]. The increasing interest in the direction of using renewable energy has led to the development of the concept of wind energy. The wind energy is a prominent renewable energy source and is a solution of global energy problem. To convert the kinetic energy of the wind into mechanical or electrical energy, wind turbines or mills have been established [3].

Most of the wind turbines basically consist of three rotor blades that rotate around a horizontal hub and convert the wind energy into the mechanical energy. The development of wind turbines for the generation of power is an an emerging area. The rotor blades of wind turbines are considered as one of the key component of the wind turbine [1]. The efficiency of the wind turbine majorly depends on the aerodynamic shape and length/angle of the blades as well as the materials used to manufacture the blades. Further, the wind turbines generate power according to the speed of the wind, not according to the demand. The basic criterion for the selection of materials for the wind turbine blades is that the material should possess high strength and stiffness, low density and adequate fatigue strength. The strength of the blade should be satisfactory so that the blade can withstand the load acting upon it without fracturing and stiff enough that it will not strike the tower during extreme loading conditions. The high fatigue strength of the blade means that it can withstand time-varying loads throughout its intended period of life. The wind turbine industries are constantly focusing on the development of light weight, cost-effective and environmental friendly materials for the production of wind turbine blades. The selection of suitable blade materials plays a significant role which determines the ultimate efficiency of wind turbine blade.

1.1 Wind turbine

Vertical axis wind turbines (VAWTs) have advantages and disadvantages, but overall they have not been commercially successful like their cousins, the horizontal axis wind turbines (HAWTs). This is largely due to the poor performance and reliability of most VAWTs. However, there are practical applications for VAWTs and new research and technology is improving their performance [4, 5].

Horizontal Axis Wind Turbines (HAWTs), on the other hand, are very advanced, reliable, and economically viable. They come in many sizes and shapes, but they are all descendents of the old windmills used to grind grain or pump water. Today these machines are proven: they are used throughout the world producing clean, affordable, and sustainable electricity. Modern horizontal axis wind turbines produce electricity 70-85% of the time (whenever the wind is over 7-8 mph).

Wind turbines are classified by their size, or "capacity" (how much electricity they can produce). They can be small (< 100 kW), intermediate (100-500 kW), or large (500 kW - 5 MW). Small wind turbines are used for homes, farms, and remote sites where electricity is hard to come by. They can be connected to the electric grid, but often they are just connected to a battery bank instead. Intermediate wind turbines are often used for schools or in hybrid systems with diesel generators used for powering remote towns and villages. Large or utility scale, wind turbines are used for producing electricity which goes onto the electric grid. We then can use this electricity in our homes, schools, and businesses [4, 5].

1.2 Development of wind energy in India

The wind energy installation is primarily concentrated in Tamil Nadu, Gujarat, Karnataka, Maharashtra, Andhra Pradesh, Madhya Pradesh and Rajasthan. Tamil Nadu has always been the leader among Indian states in the installation of wind energy. It has installed capacity of 7,276 MW wind energy, which is 34% of India's total wind energy installation. Maharashtra is closely following Tamil Nadu with 4,098 MW of installed wind energy. Gujarat, Rajasthan and Karnataka as well handsomely contributed in increasing the share of wind energy in India. All these states have installed more than 2000 MW wind energy. Wind energy has contributed more than 19,500 MW in the total installation. This is the reason, now government has increased target of annual capacity addition to 2500 MW.

1.3 Small wind turbines

A small wind turbine is a wind turbine used for micro generation, as opposed to large commercial wind turbines, such as those found in wind farms, with greater individual power output.

Smaller scale turbines for residential scale use are available. They are usually approximately 7 to 25 feet (2.1–7.6 m) in diameter and produce electricity at a rate of 300 to 10,000 watts at their tested wind speed.

Small Wind Turbine Technology Opportunities in India

There is an urgent need to coin a long-term vision of the Indian industry to produce small wind turbines that are accepted as common household appliances in the same way that Invertors and air-conditioning systems are today. By virtue of their compelling economics, these new turbines can achieve high market penetration especially in areas with lower housing densities and sufficient wind resources.

We all need to realize that large wind turbines are now in their seventh or eighth generation of technology development, while small wind turbines are yet to evolve commercially in India. Achieving these goals will require continuous advances in small wind turbine technology, progressive improvements in small turbine manufacturing, and efficient installation techniques.

For its part, the Indian industry should strive for an innovative and simple design so as to reduce the cost of electricity generated by small wind turbines in comparison to foreign small wind turbine suppliers [9]. Globally, the installed cost of a typical 1 to 5-kW residential wind turbines is about Rs. 1.5 lakhs ($3,500) per kilowatt (smaller systems being relatively more expensive). These turbines produce about 1,200 kWh per year of electricity per kilowatt of capacity in an area with a sufficient wind resource. There is a need to bring down the installed cost to somewhere between Rs.50, 000 – Rs.75, 000 ($1,200 to $1,800 per kilowatt) with raised energy productivity level to 1,800 kWh per installed kilowatt. If these goals are met, the 30-year life cycle cost of energy will be in the range of Rs. 2 kWh ($0.04 to $0.05/kWh), which is lower than virtually all-residential electric tariffs in the country today [10].

The engineering challenges presented by the interrelated disciplines of aerodynamics, structures, controls, electrical conversion, electronics, and corrosion prevention are formidable. This there is a need for adequate research cooperation between the private and public sectors to develop the small wind turbine technology indigenously.

To assist industry in addressing technology barriers, four models of Private and Public sector collaboration are proposed [11, 12].

- Research conducted at national laboratories such as C-WET, Chennai and universities with input from members of the industry.
- Applied research projects conducted at the facilities of small wind turbine companies with support from the government through competitive procurement.
- Applied research projects involving companies, universities, and national laboratories.
- Privately funded research and development.

The opportunities, which are likely to be presented by improved technology, can be achieved through the cooperative activities discussed in this roadmap for the small wind turbine industry. Work by industry members, research institutes, state and local governments, and MNES can help increase the contribution of small wind turbines to the electricity generation mix.

Ⅰ. Market potential

1.Rural electrification: The largest potential market for small wind turbines lies in those parts of rural India where the word 'electricity' is still a dream, and millions of people do not have access to electricity in their homes. In fact, three out of these five people without electricity live in far flung villages and isolated countryside hamlets, some of which are geographically isolated and are often too sparsely populated or have a too low potential electricity demand to justify the extension of the grid. Renewable energy technologies such as small Wind Turbine Power have begun to emerge as an attractive, and among the least cost and most feasible solution to provide light and power to un-electrified areas, which are too remote for grid extension [41].

2. When combined, other markets for small wind turbines in India may offer significant opportunities to expand electric generation capacity. For example, about one million medium-sized commercial buildings are strong candidates for small wind turbines of 10 to 100 kW. In addition, public facilities such as schools and government buildings could also use small wind turbines at suitable sites.

Where the utility grid is not available, stand-alone or hybrid systems could provide electricity for homes, communities, water pumping, roof top installation and telecommunications services. Some reported estimates suggest that there are around 1 million off-grid homes in India, which can immediately ignite the market for small wind systems [43].

3. In addition, it has been estimated that globally, about 2 billion people in the developing world do not have access to electricity for domestic, agricultural, or commercial uses. The traditional method of providing electricity by extending the distribution grid has proved to be expensive and purely suited to the low consumption levels of communities in developing nations. And the number of homes without electricity is increasing because the birthrate is outpacing the electrification rate [43].

4. Small-scale renewable energy systems (wind, micro-hydro, and solar) are often less expensive to install than line extensions. Small turbines are less expensive to operate and produce much less carbon dioxide per kilowatt-hour than diesel generators.

5. Can be installed on mobile phone towers, thus reducing electricity cost.

1.4 Composite Materials for wind turbine blades

Glass, carbon or aramid fibre-reinforced polymer (FRP) composites have replaced many metallic components in the various manufacturing sectors. But, the use of these materials is not considered as suitable for the environment, because these materials are highly dependent on petroleum based resources which are depleting rapidly. Due to the several environmental issues, the attention of the researchers and technologist has shifted on the utilization of natural biodegradable materials. Owing to this fact, the use of natural fibre-reinforced polymer (NFRP) composites is multiplying at a very fast pace. Recently, NFRP composites have been used as automotive parts because of their excellent combination of mechanical properties and lightweight characteristics. In addition, NFRP composites exhibit certain advantages those cannot be obtained with synthetic fibre-reinforced composites which include low density, low cost, non-abrasive properties, biodegradability and renewable nature. Natural fibres such as sisal, flax, hemp, kenaf, bagasse, banana, jute, abaca and bamboo are easily available and require low processing cost [13].

Mostly glass and carbon fibre-reinforced plastics (i.e., GFRP and CFRP, respectively) have been used for the production of large scale wind turbine rotor blades. The use of glass and carbon fibre is no more attractive to the rotor blade manufacturers, because the cost of these materials is high and the use of these materials causes environmental hazards. These attributes of synthetic fibres stimulate researchers to develop alternative materials for wind turbine rotor blades.

It is true that the wind turbine becomes the central part of the energy generation but problems come when all those wind turbine need to be replaced. The currently used materials glass, Kevlar, carbon is non biodegradable. For prevention of this large waste research effort has been made for developing biodegradable materials. Next generation best materials will be lingo cellulose based natural fiber reinforced materials.

Plant fibres offer several economical, technical and ecological advantages over synthetic fibres in reinforcing polymer composites. Due to the relative abundance, low cost of raw material, low density, high specific properties, and positive environmental profile of plant fibers like flax, hemp, coir, abaca, alpaca, bamboo and jute; they have been marketed as prospective substitutes to traditional composite reinforcements, specifically E-glass. As 87% of the 8.7 million tone global fibre reinforced plastic (FRP) market is based on E-glass composites (GFRPs)[4], Natural fibers and their composites have a great opportunity for development and market capture.

Natural Fibres

Natural fibers can be defined as substances that are obtained from plants, animals, minerals or from geological processes, which are biodegradable over time. They can be spun into filaments, threads or ropes and can be woven, knitted, matted or bound. Since natural fibers are obtained from natural sources, they do not need any formation or reformation. The commercially important natural fibers are those cellulosic fibers obtained from the seed hairs, stems, and leaves of plants; protein fibers obtained from the hair, fur, or cocoons of animals and the crystalline mineral asbestos.

2. <u>Critical Review of Literatures and identification of Research gaps</u>

2.1 Wind Turbine Rotor Blades: Construction, Loads and Requirements

Among all the parts of wind turbines (blades, hub, gearbox, generator, nacelle, tower...), composite materials are used in blades and nacelles. The main requirements to nacelles, which provide weather protection for the components, are the low weight, strength and corrosion resistance. Typically, nacelles are made from glass fiber composites [19].

The main requirements to wind turbine blade can be summarized as follows [39]

a. High strength (to withstand even extreme winds, as well as gravity load),
b. High fatigue resistance and reliability (to ensure the stable functioning for more than 20 years and 10^8 cycles),
c. Low weight (to reduce the load on the tower, and the effect of gravitational forces),
d. High stiffness (to ensure the stability of the aerodynamically optimal shape and orientation of the blade during the work time, as well as clearance between blade and the tower).

2.2 The main factors affecting mechanical performance of NFCs are:

Fibre selection – including type, harvest time, extraction method, aspect ratio, treatment and fibre content, matrix selection, interfacial strength, fibre dispersion, fibre orientation, composite manufacturing process and porosity.

(1). Fibre selection

Fibre type is commonly categorised based on its origin: plant, animal or mineral. All plant fibres contain cellulose as their major structural component, whereas animal fibres mainly consist of protein. Although mineral-based natural fibres exist within the asbestos group of minerals and were once used extensively in composites, these are now avoided due to associated health issues (carcinogenic through inhalation/ingestion) and are banned in many countries. Generally, much higher strengths and stiffness's are obtainable with the higher performance plant fibres than the readily available animal fibres. An exception to this is silk, which can have very high strength, but is relatively expensive, has lower stiffness and is less readily available [6]. This makes plant-based fibres the most suitable for use in composites with structural requirements and therefore the focus of this review. Furthermore, plant fibre can suitably be grown in many countries and can be harvested after short periods.

Generally, higher performance is achieved with varieties having higher cellulose content and with cellulose microfibrils aligned more in the fibre direction which tends to occur in bast fibres (e.g. flax, hemp, kenaf, jute and ramie) that have higher structural requirements in providing support for the stalk of the plant. The properties of natural fibres vary considerably depending on chemical composition and structure, which relate to fibre type as well as growing conditions, harvesting time, extraction method, treatment and storage procedures.

(2). Matrix selection

The matrix is an important part of a fibre reinforced composite. It provides a barrier against adverse environments, protects the surface of the fibres from mechanical abrasion and it transfers load to fibres. The most common matrices currently used in NFCs are polymeric as they are light weight and can be processed at low temperature. Both thermoplastic and thermoset polymers have been used for matrices with natural fibres [44].

(3). Interface strength

Although natural fibers are obtained from renewable sources and the polymer composites based on them are environmentally friendly, there are also some disadvantages, which are related to the utilization of unmodified/raw fibers in the preparation of the composites. These disadvantages are as quality variations, high moisture uptake and low thermal stability of the raw fibers [35-37].

(4). Fibre orientation

The best mechanical properties can generally be obtained for composites when the fibre is aligned parallel to the direction of the applied load [85–87]. However, it is more difficult to get alignment with natural fibres than for continuous synthetic fibres. Some alignment is achieved during injection moulding, dependent on matrix viscosity and mould design [88]. However, to get to higher degrees of fibre alignment, long natural fibre can be carded and placed manually in sheets prior to matrix impregnation.

2.3 Mechanical properties of natural fibre reinforced composite.

From Table No.1 it is observed that Sisal and Flax gives better mechanical properties with epoxy

Table1: Mechanical Properties of Natural Fibre Composites compared with regenerated cellulose composites and GFRP

Sl.No.	Fibre	Matrix	Fibre content (%)	Tensile strength (MPa)	Youngs modulus (GPa)	Flexural Strenth (MPa)	Flexural Modulus (GPa)	Izod Impact strength (Kj/m^2 or	Processing/Length/Treatment	Reference
1	Sisal (aligned)	Epoxy	73	410	6	320	27	27	Alkali treated bundles CM/leaky mould	[11]
2	Sisal (aligned)	Epoxy	77	330	10	290	22		Untreated bundles CM/leaky mould	[12]
3	Flax (aligned)	Epoxy	46/54	280/279	35/39				Enzyme extracted RTM	[14]
4	Harakeke (aligned)	Epoxy	50/55	223	17	223	14		CM	[15]
5	Harakeke (aligned)	Epoxy	52	211	15				CM	[17]
6	Sisal (aligned)	Epoxy	48	211	20				RTM	[18]
7	Sisal (aligned)	Epoxy	37	183	15				RTM	[19]
8	Flax (yarn) (aligned)	Epoxy	45			311	25		Not stated	[21]
9	Hemp (aligned)	Epoxy	65	165	17	180	9	15(C)	CM	[22]
10	Flax yarn (aligned)	Epoxy	31	160	15	190	15		Hand lay-up (knitted yarn)	[23]
11	Flax yarn (aligned)	Epoxy	45	133	28	218	18		Autoclave	[24]
12	Flax (aligned)	Epoxy	37	132	15				RTM	[25]
13	Flax hackled (aligned)	Epoxy	28			182	20		Pultruded	[26]
14	Flax yarn (aligned)	VE	24	248	24				RTM	[27]
15	Flax (sliver) (aligned)	UP	58	304	30				Soxhlet extracted Vacuum impregnated/CM	[29]
16	Flax yarn	UP	34	143	14	198	17		RTM (knitted yarn)	[31]

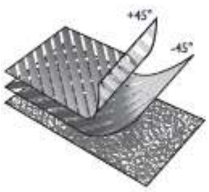
	(aligned)									
17	Alfa (aligned)	UP	48	149	12				Alkali treated then bleached	[32]
18	Flax yarn (aligned)	PP	72	321	29				Filament wound	[34]
19	Flax yarn (aligned)	PP	30	89/70	6-Jul			88/115(C)	Pultruded nax/PP yarn	[37]
20	Flax (aligned)	PP	50	40	7			751(I)	Needle punched nax/PP mats CM	[38]
21	Flax (aligned)	PP	39			212	23		Dew retted, boiled, MAA-PP coupled	[39]
22	Flax sliver	PP	44			146	15		Wrap spun flax sliver/PP hybrid yarn,	[40]
23	Hemp (aligned)	PP	46			127	11		CM	[41]
24	Kenaf selected (aligned)	PLA	80	223	23	254	22		Wrap spun, short hemp/PP hybrid yarn, CM	[42]
25	Hemp (carded)	PLA	30	83	11	143	7	9(C)	Emulsion PLA Prepreg CM	[43]
26	Kenaf (aligned)	PLA	40	82	8	126	7	14(C)	Alkali treated CM	[51]
27	Hemp (aligned)	PLA	30	77	10	101	7	19(C)	CM	[52]
28	Kenaf (aligned)	PHB	40	70	6	101	7	10(C)	Wrap spun alkali treated short hemp hybrid yarn, CM	[54]
29	Flax sliver biaxial/m ajor axis	Epox y	46	200	17	194	13		Wrap spun silver, woven, weft:wrap strength 10:1	[56]
30	Flax (woven)	Epox y	50	104	10				Sized and dried prior to pre-peg	[57]
31	Flax yarn (woven)	VE	35	111	10	128	10		RTM	[59]
32	Jute(wov en)	UP	35	50	8	103	7	11(C)	RTM	[60]
33	Hemp (biaxial)	PLA	45	62	7	124	9	25(C)	Wrap spun bleached hemp hybrid yarn	[61]
34	Harakeke (DSF)	Epox y	45	136	11	155	10	10(C)	Alkali treated CM	[62]
35	Hemp(D SP)	Epox y	50	105	9	126	8		Alkali treated CM	[64]
36	Hemp(D SP)	Epox y	65	113	18	145	10	11(C)	CM	[65]
37	Harakeke (DSF)	PLA	30	102	8				Alkali treated CM	[66]
38	Hemp(D SP)	PLA	25	87	9				Alkali treated CM	[69]
39	Flax (short-non woven)	Shella c	49	109	10					[71]
40	Harakeke (random)	Epox y	45			188	9		Alkali treated Vacuum bagged CM	[72]
41	Flax (random)	UP	39	61	6	91	5	13(C)	RTM	[74]
42	PALF (random)	UP	30	53	2	80	3	24(C)	CM	[77]
43	Wood BKP	PP	40	50	3	78	3	40(I)	MAPP coupled IM	[79]
44	Flax	PP	30			74		22(C)	MAPP coupled IM	[81]
45	Jute	PP	60	74	11	112	12	195(I)	MAPP coupled IM	[82]

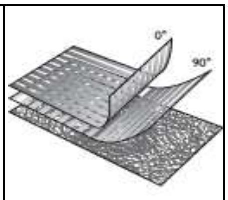
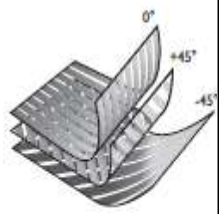
46	Newsprint	PP	40	53	3	94	4	200(I)	MAPP coupled IM	[83]
47	Kraft	PP	40	52	3	90	4	235(I)	MAPP coupled IM	[84]
48	Hemp	PP	40	52	4	86	4	210(I)	MAPP coupled IM	[85]
49	Kenaf (random)	PP	30	46	5	58	4	39(I)	CM	[86]
50	Flax	PP	30	52	5	60	5	18(C)	IM	[87]
51	Flax (random)	PLA	30	100	8				Dew retted Stripped/combed (strength 1339 MPa) Film stacking	[90]
52	Flax (random)	PLLA	30	99	9				Dew retted, stripped, combed (strength 1339 MPa) Film stacking	[91]
53	Hemp (random)	PLA	47	55	9	113				[92]
54	Cellulose (continuous)	Bio-Epoxy		92	9	727	27	26(C)	RTM	[94]
55	Cordenka"	PA	30	120	6				IM	[95]
56	Cordenka"	PP	42	90	4			87(C)	MAPP Coupled IM	[97]
57	Lyocelf (carded)	PLA	30	89	9	148	148	52(C)	CM	[98]

2.4 Multi axial reinforcement:

Multiaxial reinforcements are fabrics made up of multiple plies of parallel fibres, each laying in a different orientation or axis - hence the term 'multi-axial'.

Table 2: NCF (Non-Crimp Fabric) Multiaxial Reinforcement

Product	**Orientation axis**	**Features**	**Benefits**	**End-use applications**	
Unidirectional	0° (L) 90° (T)	Maximized axial fiber content. Improved longitudinal strength, stiffness and flex. Economical method to deliver unidirectional reinforcement. Improved strength without adding thickness at comparable stiffness.	• Reduced resin usage and part weight. • Finished parts perform under extreme tensile and flexural stress. • Lower finished part cost. • Enhanced performance from lighter laminates. • Offers design flexibility for wide range of applications.	Great for demanding applications with a high aspect ratio (length to width ratio) such as wind blades, poles, and stringers and are also commonly used in FRP pipe and fittings for increased strength.	
Biaxial	±45°	Crimp-free construction. Opposing ±45° fabric construction offers resistance to twisting. Adjustable conformability behavior.	• Improved fiber alignment and mechanical properties. • Finished parts perform under extreme shear and torsion stress. • Improved placement in complex parts.	Structural laminates including marine panel, **wind blades,** and snowboards.	

Biaxial	0°/90° (LT)	Crimp-free construction. Optimized directional fiber content. High bi-directional strength, stiffness and flex. Reduces print-through.	• Improved fiber alignment and mechanical properties. • Reduced resin usage and part weight. • Improved performance from lighter laminates.	High performance structural laminates including boat hulls, truck and trailer panels, **wind blades**, recreational sporting equipment and bridge decks.	
Triaxial	0°/±45°(TLX)	• Crimp-free construction. • Optimized directional fiber content. • Three-layer construction reduces the number of steps in lay-up. • Reduces print-through. • ±45° fiber content offers resistance to twisting.	• Improved fiber alignment and mechanical properties. • Reduced resin usage and part weight. • Reduced fabrication costs of steps. • Enhanced aesthetics with material and labor savings. • Excellent balance of axial strength and shear resistance. Offers solutions for wide range of applications.	For applications requiring a combination of axial and off-axis reinforcement including **wind blades**, boat hulls, storage tanks, trailer panels, and pultruded profiles such as bridge decks.	

3. Conclusion

The generation of energy is very essential for human survival and social development, but the generation of energy without polluting the environment is the biggest challenge of the twenty-first century. This problem can be solved by utilizing sustainable energy sources. Wind energy is the greatest example of sustainable energy source. Wind energy is clean, environmentally friendly and inexhaustible and can act as an alternative to fossil fuels. The fundamental concept of using sustainable energy lies in the fact that it can reduce greenhouse gases and pollution. It is true that wind power is the fastest growing alternative energy system, but the materials used for wind turbine components are not environmentally attractive.

As the modern wind turbines are designed for estimated life span of 20 years, a large structure need to be disposed to the environment in future after the end of service life. The materials used for wind turbines are still non-biodegradable in nature. For this reason, scientists and engineers are constantly focussing on replacing the existing material system of wind turbines with bio-degradable materials. Natural fibre reinforced composites form one such class of materials which not only possess superior mechanical properties but are also bio-degradable in nature. Natural fibre reinforced composites can be a potential candidate where they can replace the conventional material systems of wind industry. These materials can be introduced for the manufacturing of various sections of a wind turbine.

References

[1] Jimcun zhu and Hhijin Zhu “Recent Development of Flax and their reinforced composite based on different polymeric matrices” ISSN 1996-1994, 5171-5198, 2013.
[2] Girisha K G, Anil K C & Akash “Mechanical Properties of Jute and Hemp Reinforced Epoxy/Polyester Hybrid Composites” ISSN(E): 2321-8843; ISSN(P): 2347-4599 Vol. 2, Issue 4, Apr 2014, 245-248
[3] Olusegun David Samuel and Stephen “AgboAssessing Mechanical Properties of Natural Fibre Reinforced Composites for Engineering Applications” Journal of Minerals and Materials Characterization and Engineering, 2012, 11, 780-784
[5] Bénard Q, Fois M, Grisel M. Roughness and fibre reinforcement effect onto wettability of composite surfaces. Appl Surf Sci 2007;253(10):4753–8.
[6] Sinha E, Panigrahi S. Effect of plasma treatment on structure, wettability of jute fiber and flexural strength of its composite. J Compos Mater 2009;43 (17):1791–802.
[7] Liu ZT, Sun C, Liu ZW, Lu J. Adjustable wettability of methyl methacrylate modified ramie fiber. J Appl Polym Sci 2008;109(5):2888–94.
[8] Ragoubi M, Bienaimé D, Molina S, George B, Merlin A. Impact of corona treated hemp fibres onto mechanical properties of polypropylene composites made thereof. Ind Crops Prod 2010;31(2):344–9.

[9] Gassan J, Gutowski VS. Effects of corona discharge and UV treatment on the properties of jute-fibre epoxy composites. Compos Sci Technol 2000;60 (15):2857–63.
[10] Seki Y, Sever K, Sarikanat M, Güleç HA, Tavman IH. The influence of oxygen plasma treatment of jute fibers on mechanical properties of jute fiber reinforced thermoplastic composites. In: 5th International advanced technologies symposium (IATS'09), May 13–15, 2009, Karabük, Turkey; 2009. p. 1007–10.
[11] Cao Y, Sakamoto S, Goda K. Effects of heat and alkali treatments on mechanical properties of kenaf fibers. Presented at 16th international conference on composite materials, 8–13 July, 2007, Kyoto, Japan.
[12] Rong MZ, Zhang MQ, Liu Y, Yang GC, Zeng HM. The effect of fiber treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites. Compos Sci Technol 2001;61(10):1437–47.
[13] Huber T, Biedermann U, Muessig J. Enhancing the fibre matrix adhesion of natural fibre reinforced polypropylene by electron radiation analyzed with the single fibre fragmentation test. Compos Interfaces 2010;17(4):371–81.
[14] Beg MDH, Pickering KL. Mechanical performance of Kraft fibre reinforced polypropylene composites: influence of fibre length, fibre beating and hygrothermal ageing. Composites Part A 2008;39(11):1748–55.
[15] Hull, D. and Clyne, T.W. 1996. An introduction to composite materials. Cambridge University Press, Cambridge
[16] Bledzki, A. K., Reinhmane, S. and Gassan, J. 1998.Thermoplastics reinforced with wood fi llers. Polym Plast. Technol. Eng. 37:451-468.
[17] Chawla, K.K. 1987. Composite Materials. Science and Engineering. Springer-Verlag,Newyork.
[18] Andrew Cardien " Fibre glass wind turbine blade Manufacturing", 2008
[19] Colberg, M.; Sauerbier, M. Kunstst-Plast Europe Reinforced Plastics 1997, 41(11), 22.
[20] Suresh and Subba Raju "Material for typical wind turbine blade" MCDM Chaina 2006,
[21] Kishor Debanth and Inderdeep Singh "Naural Fibre reinforced polymer composites for wind turbine blade: Challenges and Opportunaties" 2013
[22] Bledzki, A.K. and Gassan, J. 1999. Composites reinforced with cellulose based fi bers. Prog. Polym. Sci. 24:221-274.
[23] Marion, P., Andréas, R. and Marie, H.M. 2003. Study of wheat gluten plasticization with fatty ac-ids. Polym. 44:115-122.
[24] Mwaikambo, L.Y.and Ansell,M.P.2003. Hemp fiber reinforced cashew nut shell liquid composites.
[25] Maya Ja cob John,Rajesh D. Ana ndjiwa la, "A rescent developments in chemical modifications and charecterization of natural fibre reinforced composites"
[26] Mehdi Tajvidi "Static and Dynamic Mechanical Properties of a Kenaf Fiber–Wood Flour/Polypropylene Hybrid Composite", DOI 10.1002/app.22093.
[27] A. Shahzad, D.H. Isaac and S.M. Alston, " Mechanical Properties of Natural Composites"
[28] Suardana, Yingjun Piao, Jae Kyoo Lim"Mechanical properties of Hemp fibres and Hemp/PP Composites: Effects of chemical surface treatmnet. December 2010
[29] H. Ku, H. Wang, N. Pattarachaiyakoop, M. Trada, "A review on tensile Properties of natural fibre reinforced polymer composites."
[30] H.N. Dhakal, "The low velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites."
[31] P.J.Herrera-Franco," Mechanical properties of continuous naturalfibre reinforced polymer composites." Composites: Part A 35 (2004)339–345
[32] Paul Wambua, "Natural fibre: can they replace glass in fibre reinforced plastics?" Composites Science and Technology 63 (2003) 1259–1264
[33] Aysegill and Biilent, "General Assessment of fibre reinforce composite selection in wind turbine blades"
[34] Darshil U Shah, "Can flax replace E-glass in structural composites? A Small Wind turbine blade case study" (2013) 172-18
[35] Rowel, R.M., Sanadi, A.R., Caul fi eld, D.F. and Jacobson, R.E. 1997. Utilization of natural fibers in composites: problems and opportunities in ligno-cellulosic-plastic composites. Eds. Leao, A., Carv-alho, F.X. and Frollini, E., USP/UNESP Publishers, Sao Paulo. pp. 23-51.
[36] Hanselka, H., Herrmann, A.S. and Promper, E. 1995. Automobil-Leichtban durchden Einsatz Von (biologisch adbanbaren) Naturfaser-verbundwerk-stoffen, VDI Berichte Nr.1235
[37] Maldas, D., Kokta, B.V. and Daneault, C. 1989. Composites of polyvinyl chloride-wood fibers. IV. Effect of the nature of fibers. J. Vinyl Technol. 11:90-99.
[38] Maldas, D. and Kokta, B.V. 1993. Performance of hybrid reinforcement in PVC composites. J. Test. Eval. 2:68-72.
[39] Hedenberg, P. and Gatenholm, P. 1995. Conver-sion of plastic/cellulose waste into composites. J. Appl. Polym. Sci. 56:641-651.
[40] Yam, K.L., Gogoi, B.K., Lai, C.C., and Selke, S.E. 1990. Composites from compounding wood fibers with recycled high density polyethylene.Polym. Eng. Sci. 30:693-699.
[41] Sain, M.M., Imbert, C. and Kokta, B.V. 1993. Composites of surface treated wood fiber and re-cycled polypropylene. Angew. Makromol. Chem. 210:33-46.
[42] Mallick, P.K. 1993. Fiber reinforced composites. Marcel Dekker, New York.
[43] Bledzki, A.K. and Gassan, J. 1999. Composites reinforced with cellulose based fibers. Prog. Polym. Sci. 24:221-274.
[44] Marion, P., Andréas, R. and Marie, H.M. 2003. Study of wheat gluten plasticization with fatty ac-ids. Polym. 44:115-122.
[45] Singh B, Gupta M, Verma A. Influence of fiber surface treatment on the properties of sisal-polyester composites. Polym Compos 1996;17(6):910–8.
[46] Beckermann GW, Pickering KL. Engineering and evaluation of hemp fibre reinforced polypropylene composites: fibre treatment and matrix modification. Composites Part A 2008;39(6):979–88.
[47] Kabir MM, Wang H, Lau KT, Cardona F. Chemical treatments on plant-based natural fibre reinforced polymer composites: an overview. Composites Part B 2012;43(7):2883–92.

[48] Bera M, Alagirusamy R, Das A. A study on interfacial properties of jute-PP composites. J Reinf Plast Compos 2010;29(20):3155–61.
[49] Gomes A, Matsuo T, Goda K, Ohgi J. Development and effect of alkali treatment on tensile properties of curaua fiber green composites. Composites Part A 2007;38(8):1811–20.
[50] Ibrahim NA, Hadithon KA. Effect of fiber treatment on mechanical properties of kenaf fiber-ecoflex composites. J Reinf Plast Compos 2010;29(14):2192–8.
[51] Goda K, Sreekala M, Gomes A, Kaji T, Ohgi J. Improvement of plant based natural fibers for toughening green composites—effect of load application during mercerization of ramie fibers. Composites Part A 2006;37(12): 2213–20.
[52] Islam MS, Pickering KL, Foreman NJ. Influence of alkali treatment on the interfacial and physico-mechanical properties of industrial hemp fibre reinforced polylactic acid composites. Composites Part A 2010;41(5): 596–603.
[53] Kabir MM, Wang H, Lau KT, Cardona F, Aravinthan T. Mechanical properties of chemically-treated hemp fibre reinforced sandwich composites. Composites Part B 2011;43(2):159–69.
[54] Sawpan MA, Pickering KL, Fernyhough A. Improvement of mechanical performance of industrial hemp fibre reinforced polylactide biocomposites. Composites Part A 2011;42(3):310–9.
[55] Hill CAS, Khalil HPS, Hale MD. A study of the potential of acetylation to improve the properties of plant fibres. Ind Crops Prod 1998;8(1):53–63.
[56] Bledzki AK, Mamun AA, Lucka M, Gutowsk VS. The effects of acetylation on properties of flax fibre and its polypropylene composites. Express Polym Lett 2008;2(6):413–22.
[57] Khalil H, Ismail H, Rozman HD, Ahmad MN. The effect of acetylation on interfacial shear strength between plant fibres and various matrices. Eur Polym J 2001;37(5):1037–45.
[58] Tserki V, Zafeiropoulos NE, Simon F, Panayiotou C. A study of the effect of acetylation and propionylation surface treatments on natural fibres. Composites Part A 2005;36(8):1110–8.
[59] Xie Y, Hill CAS, Xiao Z, Militz H, Mai C. Silane coupling agents used for natural fiber/polymer composites: a review. Composites Part A 2010;41(7):806–19.
[60] Rachini A, Le Troedec M, Peyratout C, Smith A. Chemical modification of hemp fibers by silane coupling agents. J Appl Polym Sci 2012;123(1):601–10.
[61] ickering KL, Abdalla A, Ji C, McDonald AG, Franich RA. The effect of silane coupling agents on radiata pine fibre for use in thermoplastic matrix composites. Composites Part A 2003;34(10):915–26.
[62] ranco-Marquès E, Méndez JA, Pèlach MA, Vilaseca F, Bayer J, Mutjé P. Influence of coupling agents in the preparation of polypropylene composites reinforced with recycled fibers. Chem Eng J 2011;166(3):1170–8.
[63] Jensena, R.E., Palmeseb, G.R. and Mcknighta, S.H. 2006. Viscoelastic properties of alkoxy silane-epoxy interpenetrating networks. Int. J. Adh. Ad-hes. 26:103-115.
[64] Laly, A.P. and Sabu, T. 2003. Polarity parameters and dynamic mechanical behaviour of chemically modified banana fiber reinforced polyester com-posites. Comp. Sci. Tech. 63:1231-1240.
[65] Herrera-Franco, P.J. and Valadez-Gonza'lez, A. 2005. A study of the mechanical properties of short natural-fiber reinforced composites. Composites B 36:597-608. Natural fiber-reinforced composites
[66] Abdelmouleh, M., Boufi, S., Ben Salah, A., Bel-gacem, M.N. and Gandini, A. 2002. Interaction of silane coupling agents with cellulose. Langmuir 18:3203. .
[67] Abdelmouleh, M., Boufi, S., Belgacem, M.N., Dufresne, A. and Gandini, A. 2005. Modification of cellulose fibers with functionalized silanes: ef-fect of the fiber treatment on the performance of cellulose-thermoset composites. J. Appl. Poly. Sci. 98:974-984.
[68] Abdelmouleh, M., Boufi, S., Belgacem, M.N., Dufresne, A. and Gandini, A. 2007. Short natural- fiber reinforced polypropylene and natural rubber composites: Effect of silane coupling agents and fiber loading. Comp. Sci. 67:1627-1639.
[69] Gassan, J. and Bledzki, A. 1999. Effect of cyclic moisture absorption desorption on the mechani-cal properties of silanized jute-epoxy composites. Polym. Compos. 20:604-611.
[70] Tripathy, S. Mishra, S. and Nayak, S. 1999. Nov-el, low cost jute-polyester composites. Part 1: pro-cessing, mechanical properties, and SEM analysis. Polym. Compos. 20:62-71.
[71] Mishra, S., Naik, J. and Patil, Y. 2000. The com-patibilising effect of maleic anhydride on swell-ing and mechanical properties of plant-fiber-rein-forced novolac composites. Compos. Sci. Technol. 60:1729-1735.
[72]Netravali, A. and Luo, S. 1999. Interfacial and mechanical properties of environment-friendly "green" composites made from pineapple fibers and poly (hydroxybutyrate-co-valerate) resin. J. Mater. Sci. 34:3709-3719.
[73] Gauthier, R., Joly, C., Campas, A., Gaultier, H. and Escoubes, M. 1998. Interfaces in polyolefin/ cellulosic fiber composites: chemical coupling, morphology, correlation with adhesion and aging in moisture. Polym. Compos. 19:287-300.
[74] Mwaikambo, L. and Ansell, M. 2002. Chemical modification of hemp, sisal, jute and kapok fibers by alkalisation. J. App. Polym. Sci. 84:2222-2234.
[75] Wambua, P., Vangrimde, B., Lomov, S. and Ver-poest, I. 2007. The response of natural fiber com-posites to ballistic impact by fragment simulating projectiles. Compos. Struct. 77:232-240
[76] D'Almeida, J.R.M., Nunes, LM. and Paciornik, 2004. Evaluation of the damaged area of glass-fiber-reinforced epoxy-matrix composite materials submitted to ballistic impacts. Compos. Sci. Tech-nol. 64:945-954.
[77] Hasur, M.V., Vaidya, U.K., Ulven, C. and Jee-lani, S. 2004. Performance of stitched/unstitched woven carbon/epoxy composites under high veloc-ity impact loading. Compos. Struct. 64:455-466.
[78] Lee, B.L., Walsh, T.F., Won, ST. and Patts, H.M. 2001. Penetration failure mechanisms of armour-grade fiber composites under impact. J. Compos. Mater. 35:1605-1633.
[79] Chou, S.C., DeLuca, E., Prifti, J. and Betheney, 1998. Ballistic impact damage of S2-glass-rein-forced plastic structural

armor. Compos. Sci. Tech-nol. 1453-61.
[80] Hine, P.H., Duckett, R.A., Morye, S.S., Carr, D.J, and Ward, I.M. 2000. Modeling of the en-ergy absorption by polymer composites upon bal-listic impact. Compos. Sci. Technol. 60:2631-2642.
[81] Cantwell, W.J., and Villanueva, G.R. 2004. The high velocity impact response of composite and FML-reinforced sandwich structures. Compos. Sci. Technol. 64:35-54.
[82] Rowel, R.M., Sanadi, A.R., Caulfield, D.F. and Jacobson, R.E. 1997. Utilization of natural fibers in composites: problems and opportunities in ligno-cellulosic-plastic composites. Eds. Leao, A., Carv-alho, F.X. and Frollini, E., USP/UNESP Publishers, Sao Paulo. pp. 23-51.
[83] Kazayawoko M, Balatinecz JJ. Adhesion mechanisms in woodfiber-polypropylene composites. In: Fourth international conference on woodfiber-plastic composites. Madison: Forest Products Research Soc; 1997. p. 81–93.
[84] Yu T, Jiang N, Li Y. Study on short ramie fiber/poly (lactic acid) composites compatibilized by maleic anhydride. Composites Part A 2014;64:139–46.
[85] Avella M, Bogoeva-Gaceva G, Buzˇarovska A, Errico ME, Gentile G, Grozdanov A. Poly (lactic acid)-based biocomposites reinforced with kenaf fibers. J Appl Polym Sci 2008;108(6):3542–51.
[86] Kang JT, Park SH, Kim SH. Improvement in the adhesion of bamboo fiber reinforced polylactide composites. J Compos Mater 2013;48(21): 2567–77.
[87] Bledzki AK, Mamun AA, Jaszkiewicz A, Erdmann K. Polypropylene composites with enzyme modified abaca fibre. Compos Sci Technol 2010;70(5):854–60.
[88] Sanadi AR, Caulfield DF, Jacobson RE. Agro-fiber thermoplastic composites. In: Paper and composites from agro-based resources. Boca Raton, FL: CRC; 1997. p. 377–401.
[89] Heidi P, Bo M, Roberts J, Kalle N. The influence of biocomposite processing and composition on natural fiber length, dispersion and orientation. J Mater Sci Eng A 2011;1(2):190–8.
[90] Amor IB, Rekik H, Kaddami H, Raihane M, Arous M, Kallel A. Effect of Palm tree fiber orientation on electrical properties of palm tree fiber-reinforced polyester composites. J Compos Mater 2010;44(13):1553–68.
[91] Herrera-Franco PJ, Valadez-Gonzalez A. A study of the mechanical properties of short natural-fiber reinforced composites. Composites Part B 2005;36 (8):597–608.
[92] Norman DA, Robertson RE. The effect of fiber orientation on the toughening of short fiber-reinforced polymers. J Appl Polym Sci 2003;90(10): 2740–51.
[93] Joseph PV, Joseph K, Thomas S. Effect of processing variables on the mechanical properties of sisal-fiber-reinforced polypropylene composites. Compos Sci Technol 1999;59(11):1625–40.
[94] Carpenter JEP, Miao M, Brorens P. Deformation behaviour of composites reinforced with four different linen flax yarn structures. In: Zhang D, Pickering K, Gabbitas B, Cao P, Langdon A, Torrens R, et al., editors. Advanced materials and processing IV. Stafa-Zurich, Switzerland: Trans Tech Publications; 2007. p. 263–6.
[95] Khalfallah M, Abbes B, Abbes F, Guo YQ, Marcel V, Duval A, et al. Innovative flax tapes reinforced Acrodur biocomposites: a new alternative for automotive applications. Mater Des 2014;64:116–26.
[96] Baghaei B, Skrifvars M, Salehi M, Bashir T, Rissanen M, Nousiainen P. Novel aligned hemp fibre reinforcement for structural biocomposites: porosity, water absorption, mechanical performances and viscoelastic behaviour. Composites Part A 2014;61:1–12.
[97] Angelov I, Wiedmer S, Evstatiev M, Friedrich K, Mennig G. Pultrusion of a flax/ polypropylene yarn. Composites Part A 2007;38(5):1431–8.
[98] Rodriguez E, Petrucci R, Puglia D, Kenny JM, Vazquez A. Characterization of composites based on natural and glass fibers obtained by vacuum infusion. J Compos Mater 2005;39(3):265–82.