Review Article

Application of Fully Green Bio-Composites in Manufacturing of Wind Turbine Blades: A Strategic Review

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Abstract

Energy crisis has been posing a great concern on the exploitation of limited resources and causing dramatic impact on the global economy. With the growing shortage of electricity, a rapid evolution has been observed in the wind power technology as a clean source of renewable energy. Along with considering the strength requirements and considerable forces acting on the blades of wind turbines throughout its operating lifetime, the continued growth of the industry also strengthens the need for gaining critical material knowledge for the wind turbine blades. This gives direct rise to challenges in material selection process, a major area of potential improvement. The focus of this review paper is the need for improved material knowledge, advanced, economic, and environmentally friendly materials for wind turbine blades. Present piece of research attempts to conclude various potential green bio-composites which have an edge over the existing conventional materials for the application of wind turbine blades and could prove to be a remarkable advancement in the field of wind energy. Along with the material selection, detailed insights about property requirements for wind turbine blades, problems encountered in the present-day materials, characteristics for selecting reinforced fibres, material testing, and manufacturing process of wind turbine blades have also been studied.

Keywords: Wind Turbine Blades, Bio-Composites, Natural Fibres, Biodegradable Matrix, Material Property, Biodegradability.

1. Introduction

Wind power has been receiving an increasing amount of importance worldwide as a clean source of energy. To respond to the increasing demand of electrical energy and to reduce the carbon footprints, the wind energy sector has grown exponentially throughout the years as a renewable source of energy. With the other forms of power generation, wind power industry is not only in a race to provide an aid to the countries in fulfilling the energy requirements but also in becoming economically viable form of energy with increased efficiency. Thereby power generating through wind energy will not only help the nation in fulfilling the energy requirements but also help in achieving the sustainable development goals (SDGs) [1]. Traditionally carbon fibres, glass fibres were extensively used in building of wind turbine blades, but these materials prove to be a major threat to the environment.

The worldwide demand of carbon fibre reinforced composites has risen almost 5 times and is expected to reach a tenfold increase by 2020 [2]. Metal matrix composites comprising of alloys like Nickel-Titanium (Ni-Ti), Copper-Zinc-Aluminium (Cu-Zn-Ai) etc. are also used abundantly to increase the efficiency and fulfilling the strength requirements [3].

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in the material selection process for wind turbine blades, we must go beyond what is presently possible and step up to bring changes in the material selection process.

Thereby the use of composite materials and fibre reinforcement polymers have been receiving increased attention due to their distinctive properties like light weight, great tensile and impact strength properties [5]. Among the FRPs, natural fibre composites are occupying a dominant place in the development of bio-composites because of their wide abundance and availability. Wind energy being a clean source of energy, but we cannot neglect the blades of wind turbines, manufactured from conventional materials like carbon fibres, glass fibres, aramid fibres pose an extensive threat to the environment and magnify the environmental impacts associated with their service and disposal. In order to achieve sustainable wind energy, it is crucial to consider eco-friendly materials for their manufacturing [6].

2. Property Requirements for Material Selection of Wind Turbine Blades:

One of the prime factors determining the lifespan of a wind turbine blades are its environmental operating conditions and the suitable material selection. Therefore, as a prior step to the material selection process, it becomes necessary to study the property requirements of the specified application. As shown in Fig. 1. wind turbine blades are subjected to extreme forces like wind forces and gravitational forces along with the cyclic loads throughout their operating lifetime. Not only the steady state components of the incident wind flow but the turbulence structure of the wind contributes the most uncertainty in the design and sizing of the major structural components of a wind turbine. Therefore, material possessing improved fatigue strength, tensile strength, stiffness, impact strength is required to bear the cyclic loads. In order to overcome the gravitational forces low density, light weight blade material is suitable. High strength requirement of the material is a must to resist the strong wind forces. Large stiffness is required in order to provide stability to resist catastrophic failure in extreme conditions [4]. Along with considering the thermo-mechanical properties, properties like recycling capability, biodegradability of the material, corrosion resistance, longevity of the material and the economic viability of the selected material should also be taken into prior consideration. Materials possessing these distinctive properties have a great scope in application of wind turbine blades which would thrive in achieving good aero-dynamic performance, conservation of scarce resources and reduction in environmental pollutants.

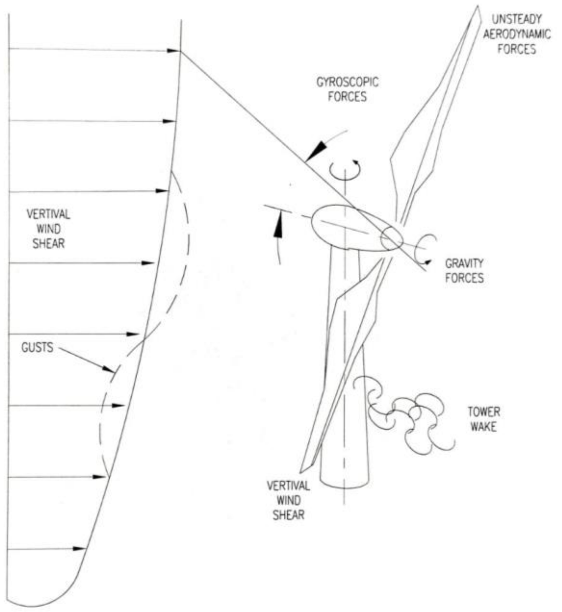

Fig. 1. Forces acting on wind turbine blade

3. Present Day Materials – Merits and Demerits

Carbon fibres, glass fibres, aramid fibres, nano composites and thermosetting polymers are some of the extensively used materials in wind turbine blades due to their superior mechanical properties like light weight, good strength, impact resistance, stiffness. However, these materials are unfavourable for the environment due to the lack of adequate information about their disposal. Advanced innovative materials like Compaxx 700 have also found a prominent place in manufacturing of wind turbine blades [7]. Other such advanced innovative material includes Elium, which is a thermoplastic resin that offers tremendous advantage of recyclability. Nanomaterials possessing high strength to weight ratio are also encouraged in the application of wind turbine blades. Nanomaterials when hybridized with natural fibres provides advantageous properties for various applications. The recycling cost of the turbine blade material is drastically reduced by the usage of thermoplastic polymers. However, thermoplastic offers disadvantage of getting deformed easily because of their high flexibility which makes it a lesser used material in comparison to thermosetting materials [4]. In addition to this, natural fibres are occupying a dominant place in the development of bio-composites. Their wide abundance, availability and distinct properties like low material cost, light weight, non-abrasive property, ease of manufacturing and reusability are attractive properties as a material choice for wind turbine blades. However, in case of natural fibres, delamination of the material is a concerning issue.

The incompatibility with the matrix material, poor adhesion, high moisture absorption property, brittle nature, low thermal stability, quality variations and presence of high cellulose content are major drawbacks.

Also, natural fibres being hydrophilic in nature, absorb high moisture content which leads to poor adhesion between the fibre and the matrix. Hence it becomes inevitable to convert natural fibres into hydrophobic nature through various treatments like acetylation, sol-gel process, adding suitable compatibilizer and carry out processes to improve the interfacial adhesion. However high strength to weight ratio, low density, high fracture toughness, wide availability, low cost, biodegradability provides them unique advantage and superiority over other materials.

4. Polymer Matrix Composite

A polymer matrix composite (PMC) is composed of a variety of short or long continuous fibres which are used as reinforcement and are bound together by a polymer matrix. Among the metal and ceramic reinforced matrix composites, polymer reinforced matrix is achieving higher attention due to its excellent properties in the application of wind turbine blades, automobile industry, aircraft industry etc. As wind turbine blades have to withstand high static as well as fatigue load, high specific strength, light weight, impact resistant, high stiffness & fracture resistant material is required, and PMCs provides all the desired properties required for wind turbine blade material [8].

Along with it, PMCs also possess good abrasion resistant and corrosion resistant property and are economically viable. Based on the conclusions drawn from the favourable advantages provided by PMCs and furthermore comparing the distinctive properties and disadvantages offered by metal and ceramic matrix composite, it could be concluded that PMCs could be one of the best material composites to be worked upon for the application of wind turbine blades. Ecological imbalance and lack of awareness is posing the world at an alarming situation at a global marketplace which obliges us to taking into consideration the toxic waste disposal issues arising at a global level. This concern has shifted researchers, engineers and all the other stakeholders in multiplying the use of polymer reinforced matrix composites. Hence the further research paves way to different kinds of PMCs.

5. Natural Fibre Composites (NFCs)

The composite prepared by reinforcing natural fibres into the matrix phase is called a natural fibre reinforced composite. NFCs possess good strength as the natural fibres bound together transfer load easily to the fibres. Natural fibres like bamboo fibres, banana fibres, jute fibres etc. are used as reinforcement in the matrix material. Many present days research work is focussed on the opportunity of using natural fibres in reinforcement polymer composites instead of synthetic fibres as results clearly show natural fibres can help reduce environmental burden drastically and still possess some of the best thermomechanical properties. In particular bamboo and banana fibres have been receiving growing attention in the field of fibre reinforcement composites.

These materials offer several advantages over synthetic fibres such as the high strength to weight ratio, tribological properties, corrosion and chemical resistance properties and ease of fabrication [9].

NFCs have immense potential in fabrication of bio-composites because of its distinctive properties like low density, adequate strength, large stiffness, large availability , non-abrasive for processing tools , provides a safe working environment , biodegradability , corrosion resistance , ease of manufacturing and excellent sound absorption efficiency are the advantages of NFCS [10]. However, despite such advantageous features, natural fibres show some important shortcomings hindering their reception like do not possess fire resistant property, property variation from specie to specie, property variation along the length, hydrophilic nature, irresistant towards chemicals. All this should be taken into prior consideration and can be efficiently eliminated by means of various methods like surface, chemical and thermal treatments or by adding suitable compatibilizers or coupling agents.

Thus, our further study focusses on the use of natural fibres as reinforcement in the composite for wind turbine blade material.

6. Bio Composites or Fully Green Composites

These composites are fully biodegradable. This are truly green and eco conscious in nature formed by combining natural fibres along with biodegradable resins or biodegradable matrices**.** Usage of renewable materials helps in developing a sustainable bioeconomy. Bioeconomy is the knowledge based on the usage of biological resources obtained from nature in various domains from products, processes and services in economic sector, health sector, agricultural sector, automotive sector etc. This provides an aid to the economy of the country to achieve a neutral carbon footprint and thereby preventing the dependency on scarce resources and thereby preventing the depletion of fossil fuels. And to address this problem bio-composites show a major breakthrough in this domain as it completely abides by the bioeconomic principles [11]. Not to forget the motto of this research lies in building a composite that is environmentally friendly and thereby eliminating the disposal issues. Considering all the above facts, it is right to conclude that bio-composites are the best material to be further worked upon for its application in wind turbine blade.

7. Characteristics of Selecting Reinforced Fibre:

Appropriate selection of natural fibres plays a vital role in forming a potential bio composite. High performance is achieved when the fibre and matrix are in optimal proportion [12]. While selecting fibre reinforcement for wind turbine blades, strength requirement must be taken into foremost consideration. Strength increases with increase in reinforcement, therefore heavier the fabric, more the strength it will possess. Strand Direction also plays a vital role, strands in omnidirectional arrangement provides greater strength is in all the directions. Along with strand**,** weave largely affects the flexibility of the material. Modified woven fabrics are found to be attractive reinforcements for wind turbine blades as they provide excellent conformity to majority of curved or streamline surfaces. Weaving patterns like knitting, braiding, plain weave, modified weave is used for weaving natural fibres using high grade technologies which drastically enhances the mechanical properties of the bio-composites [13]**.** Mechanical properties extensively depend upon the fibre composition in the composite. Fibre composition brings into play a very crucial understanding of the term that is “Hybridisation”.

7.1. Hybridisation

Hybridisation is the technique of combining 2 or more different kind of fibres in a single matrix system.

It helps in improving the thermomechanical properties of the composite. It helps in eliminating the disadvantage provide by one or the other fibre in the composite and compensates by enhancing the properties of the same. This technique is widely in practice this day and adopted by researchers, engineers etc. as it helps in drastic cost cutting of the material and improved specific properties [14]. Hybridisation comprises of mainly 2 techniques Fibre-Fibre Hybridisation and Fibre-Filler Hybridisation. This hybrid composite finds its application not only in blades of wind turbines but also in major sectors like automobile, aircraft industry, healthcare sectors, in building light weight components, sports good etc. Along with considering the above characteristics while selecting fibre reinforcement, it should be noted that fibres are hydrophilic in nature while matrix are hydrophobic hence it is important to have a prior research on the fibre-matrix bonding properties and their compatibility. However different compatibilizers and coupling agents can be used to increase the interfacial adhesion like silanes and titanates [15]. Also, several chemical fibre modifications could be made to enhance the compatibility of fibre matrix bond.

8. Natural Fibres for Fully Green Bio composites

8.1. Bamboo Fibres

Bamboo is one of the fastest growing plants in the world belonging from the grass family, its abundance gives a major advantage for considering it as a natural fibre for bio-composites. Fibres can be extracted from the pulp of the bamboo plant, which can find major applications in field of upcoming advanced reinforced fibre materials. A lot of research efforts are constantly in play in order to extract and effectively use the bamboo fibres in various domains and use them to their best of potential. Many researchers claim bamboo to be the “Green steel of the upcoming generation”. The importance of bamboo in polymer composite industry is very high due to its distinctive properties like easy fibre extraction process, favourable mechanical, thermal, and chemical properties that makes it suitable for its use in the bio-composites. It possesses adequate compressive and tensile strength; compressive strength of Bamboos is highest at the top part and low at the bottom. Irregularities in the trends are observed in tensile and compressive strength of bamboo from bottom part to the topmost part. Also, moisture content plays an important role in increased compressive strength. Tensile strength of bamboos significantly differs from one species of the bamboo to another. Whereas no significant change in compressive properties is recorded from one specie to another. That is compressive properties of bamboos remain almost same from one specie to another.

Also, one of the peculiar properties of bamboo includes being extremely light in weight that is lighter than glass fibre and about ¼ th the weight of steel, which could prove to be remarkable advancement in the fibre reinforcement in the application of wind turbine blade material. Thermal conductivity of Bamboo is also very low, being a bad conductor of heat bamboos would mainly find applications where a low rate of heat transfer takes place, considering it for high temperature resistance is yet a task. Bamboo with its large availability and being the fastest growing tree, that can grow up to around 60 cm per day can act as the best replacement as sustainable material. Major cost cutting can be done due to its large availability and abundance. Along with it , it holds great flexibility property and is earthquake resistant , hence could find its application in building materials too. Bamboo is an eco-conscious material that has the ability to absorb an immense amount of carbon dioxide giving the plant a potentially crucial role in stabilising our planet's environment. It is a fact to know that bamboo fibres can absorb electromagnetic radiations at various wavelengths which makes it exclusively less harmful to the human body [16-20]. Due to such remarkable properties offered by bamboo and its fibres, it will find potential applications in fields like wind turbine blades, building materials, casing of pumps and motors, replacement of pvc pipes by bamboos etc.

8.2. Banana Fibres

Banana fibres contains large amount of cellulose in structure and thereby provides considerable strength. Increase in tensile strength is seen as the volume fraction of fibres increases. Therefore, it is very important to pay attention to the volume fraction of the fibre as it plays a major role in determining the strength of the composite. The dynamic mechanical properties are also tremendously influenced by the volume fraction of the fibre, as optimal fibre content plays a dominant role in deciding the mechanical properties of the composite like improved tensile strength, impact strength and flexural strength [21]. It is important to note that the lower spiral angle in the structure of the banana fibre results in higher tensile strength [22]. Banana fibres can be one of the suitable choices for its fibre reinforcement in material building for wind turbine blades due to their light weight in comparison to other natural fibres. Banana and sisal fibres can be hybridised to compensate the disadvantages offered by them and help achieve the desirable properties like stiffness and good strength. By hybridising banana and sisal fibres, cost effective and environmentally friendly composite could be prepared. In addition to this, banana fibres offer good adhesion properties and compatibility with polyester matrix. Hence Banana fibres and unsaturated polyester matrix can find major applications in various domains and prove to be an excellent bio-composite in building up wind turbine blade [23].

8.3. Sisal Fibres

It is a plant fibre which is lignocellulosic in nature. The tensile strength, tensile modulus and toughness of sisal fibre increases with increase in the age of plant and decreases with increase in temperature. Wide variation in properties and strength is observed which reduces the possibility of using these fibres for applications that require high reliability and consistency. However tensile strength, modulus, and toughness of sisal fibre reduced at 100 degree Celsius which makes it suitable to be used as a reinforcing filler material for various application around 100 degree Celsius. In addition to this, sisal fibres are light weight fibres and possess remarkable sound attenuation characteristic which can make it a suitable natural fibre in application of wind turbine blades in damping of the sound produced by the rotor [24]. However, sisal fibres cannot be used alone due to the poor strength properties possessed by it at high temperatures, however various treatments can be undertaken to enhance the properties of sisal fibres. Thermal treatment or surface treatment of boiled sisal fibres in 18 % NAOH provides higher tensile and flexural strength and increases the mechanical properties of the composites.

Sisal fibres are also highly chemical resistant towards all the chemicals except carbon tetra chloride providing it an edge over the other natural fibres [25]. Also as discussed above, fibre orientation plays a vital role in deciding the mechanical properties of the composite material, hence from the literature review it was found that 0 degree and 90 degree (bidirectional) treated sisal fibre reinforced in unsaturated polyester resin have better tensile and flexural strength than 0 degree and ±45 degree [26].

8.4. Jowar Fibres

Jowar is abundantly available in parts of Asia, especially in India. The density of jowar fibre is quite low which can be readily used in designing lightweight materials. Jowar fibre composite possess good tensile strength at highest volume fraction of fibre. The mean tensile strength and specific tensile modulus of jowar fibre composite at highest volume fraction of fibre is found to be higher in comparison to sisal composites and almost equal to bamboo composite. Other than mechanical properties it is a sustainable material possessing properties like good economic viability, ease of manufacturing properties and is available in great abundance. Hence development of jowar fibres with polyester matrix can be a viable material option for wind turbine blades because of the great specific properties provided by jowar fibres [27].

8.5. Flax Fibres

Flax fibres are a cellulose polymer-based fibre consisting of high content of cellulose. Higher the cellulose content, greater the strength it provides. Thereby flax fibres possess favourable properties like great tensile strength, water retention property, vibration absorption properties, cost effective and environmentally friendly.

The main drawback of the fibre is the bad compatibility with most of the matrix material, which could be improved by using suitable coupling agents or compatibilizers. Also, flax fibres do not possess good thermal stability as fibres start degrading at high temperatures, they are also sensitive to water and needs an efficient drying process. De-waxing and several surface treatments also becomes crucial in case of flax fibres which is a major demerit. Hence it could not be a potential fibre for the application of wind turbine blades, major reason include it cannot sustain the high temperature offered [28].

8.6. Jute Fibres

Jute possesses high lignin content. Jute fibre does not possess good mechanical properties. The tensile strength of jute fibres is low. The main advantageous property of jute fibre is that it is fire resistant. Jute fibres possess excellent adhesive property with polylactic acid matrix material [29].

8.7. Hemp Fibres

Hemp fibre is a natural lignocellulosic fibre (NLFs). It possesses higher strength with matrix material like epoxy and polyester. The superior tensile strength of 50.5 MPa, flexural strength of 76.7 MPa, modulus 3.8 GPa) and elastic modulus of 1.72 GPa is achieved for 30 vol% hemp fibre in epoxy composites [30]. Hemp fibres also possess good adhesion properties with polyester but the tensile and flexural strength of hemp fibres decreases with polyester matrix. Also, it doesn’t possess good impact strength which makes it unsuitable for the application of wind turbine blades which suffers high impact loading during the entire operating life. [31]

8.8. Kenaf Fibres

Kenaf fibres possess favourable mechanical property of low density and high strength which is a crucial property requirement in building of wind turbine blades. Kenaf fibre with a density of 1.4 g/cm3 possess strength in range of 284 and 800 MPa and a modulus ranging between 21 and 60 GPa , which is a desired good weight to strength ratio.

Although the following strength is not favourable for most of the engineering applications hence reinforcing kenaf fibres with glass fibres and addition of nano clay up to 2-4 % (less than 5%) brings a significant change in the mechanical properties including tensile and flexural strength [32].

8.9. Pineapple Leaf Fibres (PALF)

Pineapple leaf fibres are a form of agro waste that could be used as a prominent natural fibre. It is hygroscopic in nature. The pineapple leaf fibres possess good strength and can be used as replacement of softwood. PALF are rich in cellulose thereby they show astounding mechanical properties like higher tensile strength and young modulus [33].

8.10. Corncobs

Corn cobs possess good hydrophobic characteristics. The properties greatly depend on the size of the corn cob particles. The rougher surface of the corn cob particles provides mechanical adhesion between fibre and matrix by interlocking action, which improves the strength of the composites. It should also be noted that cracks occurred in the matrix during the drying step, which indicates that fibre-matrix adhesion is stronger than the cohesion of the matrix itself [34]. However mechanical properties like high tensile strength, flexural strength and impact strength can be largely enhanced by mixing corn cob with equal ratio of wood powder. Also, the addition of corn cob with wood powder reduces the voids and cavities and provides greater compatibility and adhesion between them. Studying the specific properties provided by corn cobs after hybridising it with wood powder and using suitable matrix material and coupling agents, it could be a primary choice in applications like interior of automotive, furniture parts, wind turbine blades etc [35].Coir, cotton, roselle, ramie, okra, protein fibres, abaca , sugarcane bagasse are few other natural fibres that could be explored for building up bio-based materials or bio-composites.

9. Biodegradable Matrix Materials

Selection of matrix material is a very crucial part of forming bio-composites. It keeps the reinforcements in place and plays an important role in the phenomena of load transfer from the surface of the composite to the fibre reinforcement phase. In addition to this it also provides environmental protection to the fibres from the outside harsh conditions. It also provides chemical resistance and resistance against mechanical abrasion to the fibres. Matrix material can be widely classified into two type that is synthetic polymer matrix material and biodegradable matrix materials / biodegradable resins.

Synthetic polymer matrix is further classified into thermoset polymers, thermoplastic polymers, and elastomers. Thermosetting polymers are extensively preferred in wind turbine blades owing to their distinct properties like good adhesion and compatibility with most of the fibres, low high strength-to-weight ratio and performance, outstanding dielectric strength, low thermal conductivity, resistance to corrosion effects and water, high heat resistance and reduced production costs over fabrication. However, the use of this polymers is discouraged as they are a major threat to the environment and causes disposal issues over the passage of time. Thermoplastic polymers are known for its versatile properties and recyclability. The other advantages of using thermoplastics include high strength, light weight, ability to withstand corrosion and can withstand high temperatures. However, development of thermoplastics in the field of composites is still in its primary stage and there is a deep scope of research that would introduce a new composite possessing properties of both -strength of thermosets and versatile recyclability property like thermoplastics [36].

9.1. Polybutylene Succinates (PBS)

Polybutylene succinates (PBS) is one of the most promising polymers amongst all which is chemically synthesized by the polycondensation of 1,4-butanediol with succinic acid [37]. Due to its biodegradability, excellent processability, thermal and chemical resistant properties, toughness, good thermal stability at high temperatures it finds its application in various potential fields. However improved specified mechanical properties can be obtained by reinforcing PBS with fibres. Fibres like bamboo, sisal, curaua, banana, kenaf are potential fibres that can be used as reinforcement along with PBS to achieve best mechanical properties [38]. According to the literature review, bamboo, sisal and curaua fibres can build up into a potential bio-composite with PBS due to its superior chemical compatibility with the aliphatic matrix as well as to the surface morphology. Both these factors contribute to the formation of a strong interface between them, making the composite capable to effectively transfer the load from the matrix to the fibres. Sisal/PBS and curaua/PBS composites also showed greater resistance against water absorption in comparison with other natural fibres reinforced with PBS matrix [39]. Hence to sum up PBS with remarkable properties like biodegradability, light weight, high strength, increased impact and tensile properties is one of the most suitable matrix materials for manufacturing of wind turbine blades. In addition to this blending, it with polylactic acid helps in acquiring increased impact and tensile strength without changing its thermal properties.

9.2. Polybutylene Succinate Adipate (PBSA)

Polybutylene succinate-co-butylene adipate (PBSA) is a combination of 1,4-butane diol, succinic acid, and adipic acid. It is prepared by adding adipic acid to source materials during PBS synthesis. The major difference and advantage of PBSA over PBS is: PBSA degrades faster than PBS and has lower crystallinity, which is better suitable for film applications, on the other hand PBS has higher crystallinity which is better suitable for moulding application [37]. PBSA reinforced with bamboo fibres provides improved mechanical, biodegradable and morphological properties. Also, this are fully green materials which provides an edge over other materials. The only major drawback of bamboo fibres includes dried bamboo fibres ranging in length from millimetres to a centimetre do not blend well in polyester matrices and require a compatibilizing agent or coupling agent to wet the fibres. This could be overcome by using PBSA which has higher hydrophilicity, resulting in natural wetting of bamboo fibres. Also, PBSA-g-AA and bamboo fibre composites exhibits higher resistance to water absorption than PBSA and bamboo fibre composites and it is proposed that the interaction of AA-grafted PBSA with BF increased the hydrophobicity of BF in this blend. Hence composites of polybutylene succinate adipate (PBSA) and bamboo fibres overcomes major hurdle of hydrophilicity property of bamboo and provides advantages in both compatibility and reduction in cost [40].

9.3. Unsaturated Polyester

Polyester amides are formed as a result of combining ester and amide linkage in a chain. Owing to the properties of both polyamide and polyester family, this are biodegradable and are particularly attractive for the application of wind turbine blade because of their high thermo-mechanical properties. Unsaturated polyester is a crucial biodegradable matrix in the field of bio-composites as it also has excellent bonding property and compatibility with most of the natural fibres like sisal fibres, jute fibres, bamboo fibres, kenaf fibres etc. Unsaturated polyester reinforced with kenaf fibres shows remarkable properties for application in various domains [31]. Kenaf fibres reinforced with polyester possess higher tensile modulus and tensile strength in comparison to bamboo polyester composite and jute polyester composite. However, bamboo-polyester and jute-polyester composite have similar tensile modulus and ultimate strength [41]. It also possesses good resistant towards chemicals, ageing, weathering, and water.

9.4. Polylactic Acid (PLA)

Polylactic acid (PLA) is one of the best and attractive polymers because of its biodegradability property and great adhesive property. It has a higher tensile strength and elastic modulus in comparison to other polymers.

The major demerits of PLA include its brittle nature, lower toughness, lower impact strength and high cost when used alone without reinforcing fibres. PLA are also easily breakable on elongation which limits its application in several domains. However, using polylactic acid with natural fibre reinforcements shows distinctive enhanced properties [42].

Tensile strength, tensile modulus, flexural strength, and flexural modulus of polylactic acid increases with the addition of jute fibres. The Tensile strength and flexural strength of composite at 15% fibre loading was about 25% and 116% higher than the plain PLA, respectively. The tensile modulus and flexural modulus of the jute and PLA composite at 15% fibre loading was 1.55 and 1.87 times that of plain PLA respectively which makes it one of the suitable bio-composite for application of wind turbine blades owing to good tensile and flexural strength offered by it along with its biodegradability property [29].

9.5. Polyglycolic or Polyglycolide Acid

Polyglycolic acid is a biodegradable and thermoplastic polymer. It possesses the greatest strength out of most of the biodegradable matrix materials. This makes it an important matrix material for various applications including wind turbine blade material along with suitable fibre selection [31].

10. List of Fully Green Bio composites – Fibre / Matrix Combination

Based on the overall literature study, Table 1. provides the list of natural fibres and biodegradable matrix materials that build up to form potential fully green bio composites and finds varied applications in distinctive domains.

Table. 1. List of fully green bio-composites – potential fibre / matrix combination

SR. NO	FIBRE MATERIAL	MATRIX MATERIAL
1.	Bamboo Fibres	Polybutylene Succinate (PBS)
2.	Bamboo Fibres	Polybutylene Succinate Adipate
3.	Banana Fibres	Unsaturated Polyester
4.	Jute Fibres	Polylactic acid
5.	Hemp Fibres	Polybutylene Succinate (PBS)
6.	Sisal Fibres	Unsaturated Polyester
7.	Sisal Fibres	Polybutylene Succinate (PBS)
8.	Flax Fibres	Polybutylene Succinate (PBS)

11. Material Testing

Material testing is a crucial part of the process and includes a variety of mechanical, thermal, and analytical tests. The primary test required for material testing of wind turbine blades include static tensile test, static compressive test and shear tests. Shear tests include interlaminar shear test and in-plane shear test. Along with static loads, very large number of fatigue cycles and impact load is experienced by a wind turbine rotor and other structural components during the entire turbine operational lifetime hence fatigue test, Izod impact test and flexural testing must be performed.

In case of bio-composites testing specific gravity, moisture content test and water absorption test are inevitable as natural fibres are hydrophilic in nature and absorb large amount of water as discussed earlier (17). Secondary tests include vibration and non-destructive tests. Other advanced tests carried out in high tech labs include determination of reactivity by means of differential scanning calorimetry (DSC), characterization of visco-elastic properties by resin rheology tests and dynamic mechanical analysis (DMA) is used to measure thermal properties of cured laminates. Mechanical properties are measured by means of G1C and K1C test which helps to determine fracture toughness of the material [43].

12. Composite Manufacturing Processes for Wind Turbine Blade

Manufacturing processes greatly determine the operating life cycle of the wind turbines. It can introduce conditions in the composite that greatly influences its fatigue life.

Major problems include local resin content variations, local fibre curvature, prior to cure, if the viscosity of the resin is low than it can move around in the assembly due to the forces of gravity or slight differentials in bag pressure or fibre tension. This will result in large variations in resin content in the composite. Some areas will have low resin content while some will have large resin content, this will lead to unequal lowered strength of the composite, making it prone to deformation, failure, development of crack etc. Hence it is very important to select the right manufacturing process for the right application.

There are mainly 3 types of composite manufacturing processes: open moulding, closed moulding and cast polymer moulding. The following is a brief discussion on the current and most convenient and efficient method for manufacturing of composite wind turbine blades. The small and medium blade are mainly manufactured by manual processes like hand lay up or wet layup method. While large blades are manufactured using Resin Transfer Moulding (RTM) or Pultrusion process. Out of the many manufacturing processes, below listed are the few efficient methods of composite processing for manufacturing wind turbine blades.

12.1. One Shot Blade Technology

One shot blade technology is an innovative method of manufacturing of wind turbine blades. This is one of the most reliable and efficient method for producing wind turbine blade. As shown in Fig. 2. One shot blade technology produces one-piece structure through a single infusion which leads to substantial time saving in comparison to conventional manufacturing processes.

This innovative technology focusses to reduce and simplify each step in the production process and provide higher strength by eliminating the bonding process.

It significantly reduces the wastage of material which in turn reduces the manufacturing cost and labour hours.

Along with it, the principal benefit of using the presented technology is the absence of any kind of adhesive to produce the blade which improves the reliability of the structure and reduces the production as well as maintenance costs [44].

Fig. 2. Conventional blade vs One Shot blade technology

12.2. Hand Lay-Up Method

Hand lay-up is an open moulding method. It is the simplest composite moulding method for manufacturing of wind turbine blades. As shown in Fig. 3. coating of gel is first applied to the mould manually or by using a spray gun for a high-quality surface. When the gel coat has cured sufficiently, fibre reinforcement is manually placed on the mould.

The laminating resin is then poured in. FRP rollers, paint rollers, or squeegees are used to consolidate the laminate, thoroughly wet the reinforcement, and most importantly removing the entrapped air. Furthermore, reinforcements are added to build up the laminate thickness according to the strength requirements.

This method is the most suitable method for manufacturing of small and medium wind turbine blades as it offers the following advantages like low cost, ease of processing, minimum investment, consistent quality and good production rates [45].

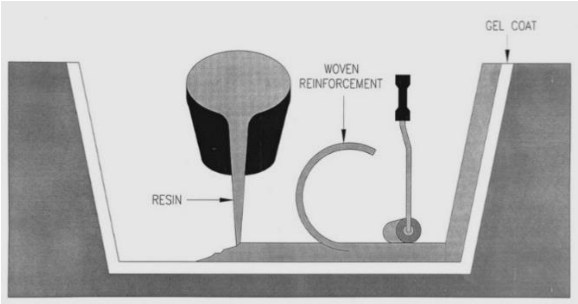

Fig. 3. Hand lay-up method.

12.3. Resin Transfer Moulding (RTM)

As shown in figure 4. In this process resin is injected under pressure into a mould cavity. The mould is first coated with gel for easy de-moulding of the composite. The Reinforcement material is then laid inside the mould and clamped. Vacuum assist can be used to enhance resin flow in the mould cavity. The resin is injected under pressure, using injection equipment and the part is cured in the mould.
The reinforcement can be either a preform of wind turbine blade geometry, a preform is a reinforcement that is formed to a specific shape in a separate process and is quickly positioned in the mould. Thickness of the part is determined by the tool cavity. This process produces parts with two finished surfaces and hence is efficient for manufacturing of medium to large wind turbine blade composites with good surface finish and quality construction. [46]

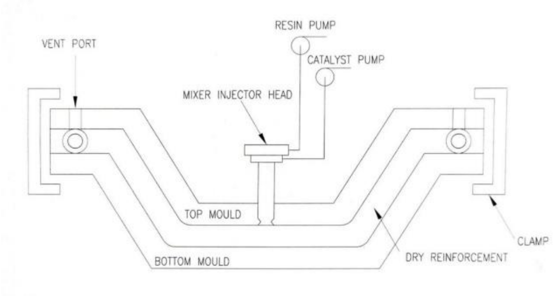

Fig. 4. Resin transfer moulding process [RTM].

12.4. Pultrusion

Pultrusion is one of the best methods to manufacture products with constant cross section or structural shapes like wind turbine blades. Pultrusion produces profiles with extremely high fibre loading thus by this method high structural properties could be achieved. As shown in figure 5. continuous strand fibres are impregnated in a resin bath and then pulled through a steel die by a powerful tractor mechanism.
The steel die consolidates the saturated reinforcement, sets the shape of the stock, and controls the fibre and resin ratio. The die is heated to rapidly cure the resin. Many creels (balls) of roving are positioned on a rack, and a complex series of tensioning devices and roving guides direct the roving into the die. The quality of the laminate or composite achieved by this method is excellent [45].

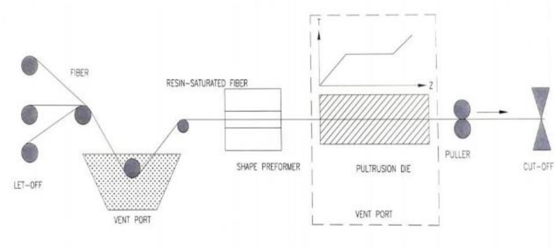

Fig. 5. Pultrusion process.

Conclusion

From the literature study it could be concluded that natural fibres embedded into biodegradable matrix (fully green bio-composites) have immense potential to replace synthetic fibres and traditional materials in manufacturing of wind turbine blades. Sisal fibres reinforced with polybutylene succinate (PBS) and bamboo fibres reinforced with polybutylene succinate adipate (PBSA) matrix material possesses the most favourable characteristics like high strength to weight ratio, low density, good tensile strength, compressive strength, high flexibility , thermal and chemical resistant properties, toughness, good thermal stability at high temperatures and biodegradability and are one of the most suitable fully green bio-composite for manufacturing of wind turbine blades.
Undertaking the hybridisation technique, banana and sisal fibres with unsaturated polyester matrix using suitable compatibilizer also enhances the specific properties offered by each other like good tensile strength, light weight, recyclability etc. making it another notable bio-composite material for the application of wind turbine blade. For the manufacturing of wind turbine blade composites, it could be concluded that one shot blade technology is one of the most reliable and efficient method of processing high strength wind turbine blades. Provided the entire study concentrates on escalating the use of fully green bio-composites without compromising on the property and strength requirements and thereby also eliminating the disposal issue and environmental threat posed by conventional materials. Hence using natural fibres and biodegradable matrix could prove to be a promising work in building up fully green bio - material for wind turbine blades.

The authors do not have any conflict of interest.
The datasets analysed during the current study are available from the corresponding author on reasonable request. All the data analysed during this study are included in this published article in the references as mentioned and can be accessed from there.

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