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Review

Recent Trends in Preparation and Applications of Biodegradable Polymer Composites

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Abstract: This review efficiently covers the research progress in the area of polymer bio composites in perspective of the modern-day renewable materials. In the last decade, attraction towards the bio-composite based systems has been the topic of interest due to their potential as a substitute of conventional materials produced in important manufacturing industries. Recently, preparation of biocompatible and biodegradable polymer composites is an important achievement as an alternative of petrochemical based renewable products. Successful production of eco-friendly bio-composite materials have been achieved with natural fibers viz jute, bamboo, hair, flex, wool, silk and many others instead of synthesized fibers like carbon, glass dispersed in synthesized resins viz poly vinyl alcohol, epoxy and etc. Biomaterials based on natural fibers dispersed in natural matrix like natural rubber or polyester have also been obtained with endless applications for the mankind. The utilization of such materials for the good well of mankind is attributed to their ease of disposal and being renewable. The last but not the least, the extraordinary mechanical properties of bio-composites make them superior to many other conventional materials. This review paper addresses the recent trends, mechanical and chemical properties, synthesis, and application of bio-composites in the recent years.

Keywords: Renewable; bio-composites; eco-friendly; composites

1 Introduction

Most recently the critical problem of the recycling of non-biodegradable material has led the world interest towards preparation of biomaterials with keen focus on renewable and biodegradable raw materials. This is because the use of traditional polymer composite materials, usually made by dispersing glass, carbon or aramid fibers in epoxy, polyester etc., is considered critical being responsible for the deterioration of environment health. So, bio composites with bio fibers as reinforcing materials are designed to encounter different necessities. These natural fibers are cheap on one hand and are biodegradable on other, as a consequence Bio-composites materials have made scientists to think a possible solution to cope with problems of waste-disposal problems linked to traditional petroleum-derived plastics [1].

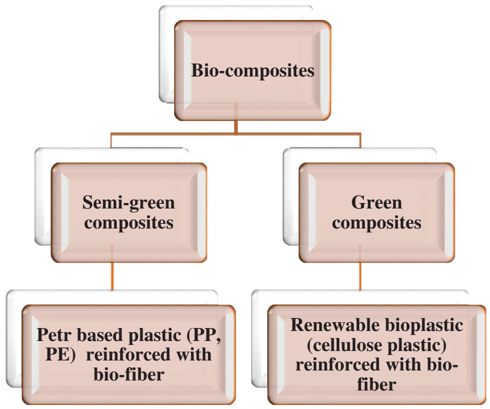

Figure 1: Classification of bio based composites

Bio-composites are composite material made from bio fibers (natural fibers) and petroleum derived non-biodegradable polymer like Polyethylene (PE), Polypropylene (PP), Polycarbonate (PC) and epoxy derivatives or biopolymers like Polylactic acid (PLA) and Polyhydroxyalkanoates (PHAs). Similarly, composite materials prepared from biopolymer as matrix while synthetic fibers such as glass and carbon also come under the category of bio-composites Fig. 1.

Bio-composites derived from botanical sources (natural/bio fiber) and biopolymer are more ecofriendly, such bio-composites are sometimes termed as "green composites." Use of natural fibers as filler have gained keen interest over conventional synthetic fibers due to their low density, Low cost, comparable toughness, strength and properties like ease of separation and biodegradability. Ecofriendly green bio-composites have proved themselves as the new material of 21st century and provide a plausible and valuable solution to many environmental problems [2].

There are number of factors, e.g., type and quality of fiber, environmental conditions in which the fiber has sustained, processing and modification methods of the fiber, that affect bio composite's properties. Biopolymers in most of the cases are used as a matrix for bio fiber reinforced composites and have endless industrial applications [3].

After several years of research, today high-performance bio-composites are produced. Bio fibers especially botanical fibers of bast and leaf have shown a great number of applications in automotive parts of machinery. Along with them some fibers have not yet been explored sufficiently for their large-scale commercial applications, i.e., fibers made from seed and animals (chicken feather, fish scales). The reason being less research into them is because they are secondary or made from waste products [4].

Due to sustainability benefits, bio fibers such as botanical fibers are taking on account of synthetic fibers in various composites. Recently, starch as a filler in bio-composites has received much attention due to its total compatibility without any toxic residues, low cost, and wide availability. But the main problem with starch-based polymer is their low mechanical strength and high moisture absorptivity. These fundamental properties of starch filled polymers needs to be enhanced to make such materials to be truly market demanding compared to commonly used conventional petroleum-based polymers. To achieve this goal one of the most promising and sophisticated technical advancement has been the use of nanofillers for development of Nano-bio composite [5].

Nowadays, technological advancement triggers researchers to invent synthetic biopolymers with improved chemical, mechanical, morphological and barrier properties, which not only overcome the drawbacks of natural polymers but also include other properties that help to enhance food safety, quality, and shelf-life. Moreover, due to environmental sustainability issues, a good hand of research work has been seen in the use of bio-composites over the past few decades. There are a great number of achievements in ecofriendly technology in the field of materials science through the preparation of of bio-composites like in automotive and decking markets, but the applications of these composites in other sectors has been seen limited. However, with suitable developmental techniques and utilizing knowledge of science, the potential exists for bio-composites to be used in new markets [6].

2 Composite Materials

Composite materials which are sometimes referred as composition materials or simply as composites. No single material can satisfy the demands of today's world because the demands required by the industries for such materials to exhibit excellent performance are so many and diverse. This eventually led the world to the perception of combining effect of different materials to generate a composite system that resulted in a performance that could never have been possible to achieve by the use of individual constituent. This indicates that, a composite material can meet the needs of several engineering applications compared to single material whether a polymer system or ceramic [7].

The mist common composite materials are composed of two or more constituents with considerably different set of physical and chemical properties, filled, mixed and bonded on macroscopic, microscopic and Nano level. The new composite material produced exhibits better and advanced material properties and strength than the individual materials [8]. Generally, a composite material is composed of reinforcement phase used as filler and a matrix phase or dispersion medium. Reinforcement material also referred as dispersed phase like fibers, particles, flakes, sheets etc. is entrenched in a matrix hase like polymers, metals, or ceramics. The matrix surrounds and holds the filler to form the desired shape and also protect it from environmental attack while the dispersed phase or filler is responsible for improvement in the bulk mechanical properties of the matrix [9].

2.1 Reinforcing Phase

In most of the composite materials the reinforcement phase has larger size to volume ratio, stronger, harder, and stiffer as compared to matrix. It may be a fiber or a particulate. Particulate composites have been seen with approximately equal dimensions and dispersion in all directions. However, the geometry of particulate composites may vary from spherical to any other regular or irregular form. The strength of particulate composites is weak as compared to fiber composites, but they are much less expensive. On the other hand, fibers based composites have shown high-strength because of their small diameter. The lesser diameter and larger volume of the fiber results in greater strength of the end material, but with a drawback, with a cost increase as the diameter becomes smaller. Typical fibers include cellulose, glass, aramid, and carbon, which may be continuous or discontinuous [10].

2.2 Matrix Phase

Dispersion medium or the matrix phase which is always a continuous phase. The continuous phase may be a metal, polymer or ceramic. Comparably, polymers have low mechanical strength and stiffness while metals possess intermediate degree of strength and stiffness with high ductility, and ceramics exhibit highest mechanical strength and stiffness but are brittle. The function of matrix phase is to maintain the fibers in the proper orientation and protect them from any external environmental attack. The fiber and the matrix are bonded together with strong intermolecular and chemical interactions. The overall strength of the composite is due to transfer of loads from the matrix to the fibers through shear loading at the interface. As in ceramic matrix composites there is a little issue of strength, the objective is here to increase the toughness and elasticity rather than the strength and stiffness; therefore, a low interfacial strength bond is desirable [11].

2.3 Merits and Demerits of Composites

- Ecofriendly and non-toxic.
- User friendly and have low cost.
- Biodegradable, compostable.
- Non-abrasive.
- Light weight/small density.
- Income Source for agricultural community.
- Temperature and noise insulating property.
- Biodegradable and renewable raw materials.
- Free from hygienic hazard.
- High strength and thermal properties.
- High and excellent toughness.

Some disadvantages of composite materials are as follows:

- Less compatible with organic polymer matrix.
- Deterioration of fiber due to packing for a long time period.
- Absorptive [12].

Although the composite materials have many advantages and are far more efficient than individual materials, but downside is often the cost. The starting materials in form of fillers or matrices used for the preparation of composites are often very costly [13].

The concept of composites is centuries old and has been used in ancient times by nature for millions of years. These Ancient societies used this approach as well: The Book of Exodus explain that ancient people use straw to reinforce mud in brickmaking, without straws bricks would have almost no strength [14].

2.4 Applications of Composite Materials

- In Aerospace industry- Roughly more than 50% components of the airspace ships are made from polymer composites. The main function of composite materials is their light weight and assembly simplification. Composites materials are now using at large scale in helicopters, civil transport aircrafts, satellites etc. Most of the components of aircraft that is airbrakes, elevators, wheel, spoilers, doors, keel beam, wings, turbine engine, blades of fan etc. are made of composite material [15].
- In Automotive industry- Polymer composites are largely used to make very light, corrosion resistant, harmless, and more fuel saving vehicles. Most of the bodywork elements of vehicles like wheels, engine cover, steering, console, seat, ceiling, foot mats, heat absorber, interior and exterior panel, etc. are manufactured by polymeric composite materials [16].
- In Electrical industry- The composites are utilized to fabricate electrical contacts, connectors, heat descends, circuit boards, interlayer insulations, current interface materials, etc. Due to high strength, high modulus, greater heat conductivity, low coefficient of thermal expansion, low value of dielectric constant and controllable electrical conductivity required for particular electronic applications these composites materials have key role in electrical field [17].
- In Medical- Composite materials are widely used in medical devices. Surgical techniques, synthetic materials, and decontamination and sanitizing methods have allowed the use of composite material in a variety of ways. Composites are now used in the artificial bone and joint scaffolds, artificial heart valves, pieces for dentistry, muscles of pacemakers, as biosensors, eye lenses, artificial hearts, widely

used to replace or restore the function of degenerated organs or tissues, to improve function, to help in healing, to correct abnormalities and thus improve the quality of life of the patients [18].

- In Sports- Due to light weight, high strength, ease of transport, corrosion and friction resistance, high thermal stability and durability composite materials are widely used in sports equipment. From very old times, natural materials, like wood and grass, were being used to make sports articles due to its ease of availability, nice shock absorption and ease of molding to any shape, but these materials showed many drawbacks like high moisture absorption and low resistance. These conventional natural materials are now replaced by goods made of composite materials. These goods includes common tennis rackets, badminton rackets, boards for sailing, plastic bats, ice hockey sticks, footballs, wrestling boards, bows and arrows etc. [19].
- In Chemical Industry- Due to fire retardant properties, lightness, ease of molding, and high chemical resistivity has made these composites material as the component of choice in chemical industry. These composites are extensively used for fabricating many important equipment like columns, reactors, industrial grills, drain stacks, propels & blowers, piping storage tanks, structural supports, finishers, ducting, piping etc. [20].
- Space application- Composites along with nanotechnology are an emerging research area to develop multifunctional materials for space applications. For prolonged space missions we need light weight accessories, which can only be achieved by replacing metallic structures of spaceships, satellites etc., with composites [21].
- Other- Composites are being used in the structural parts of buildings, industrial supports for many industries, roof structures, storage tanks, various components of bridge with complete bridge systems. Considerable success has been achieved in making light weight doors, windows, and furniture based on composite for domestic and other construction purpose [22].

3 Classification of Composite Materials

A brief classification of Composite materials according to type of constituents used is shown here [23], Fig. 2.

3.1 Classification According to Type of Matrix Material

Based on matrix the composites can be classified as metal matrix, ceramic matrix, and polymer matrix composites [24], Fig. 3.

3.1.1 Polymer Matrix Composites (PMCs)

Polymer matrix composites consist of polymer (e.g., epoxy, polyester, urethane), reinforced by thin diameter fibers (e.g., graphite, aramids, boron). PMCs are developing rapidly because the manufacturing of PMCs does not need any complicated equipment, high pressure, and temperature. But strength and stiffness of PMCs are low as compared to metal and ceramics matrix composites. These deficiencies are covered by reinforcing other materials with polymers [25–27].

Polymer matrix may have thermoplastic polymer or thermosetting polymer with fillers used as dispersed phase of carbon, glass and metal fibers [28–31]. Thermosetting polymers are more important and matrices of interest than common thermoplastics due to their higher mechanical strength and insulating properties [32]. Epoxies have more demanding applications and have been the commonest thermosetting matrix material [33]. Thermoset polymers are prepared by mixing fluid resin with some sort of hardening agent. Laminated structure is most widely used as filler for PMCs made by loading and bonding thin layers of polymer and fiber, the process is carried on until the anticipated thickness is achieved. These PMCs are extremely low cost composites because the fabrication methods are simple and use of convenient handling techniques [34–35].

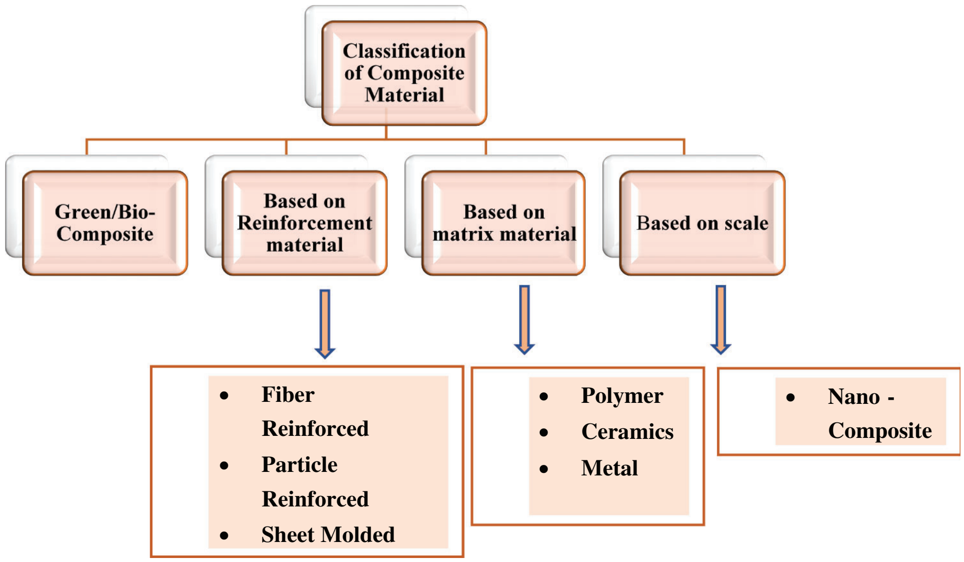

Figure 2: Classification of composite materials

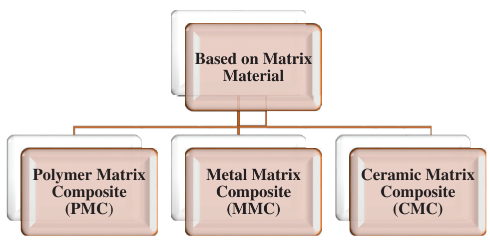

Figure 3: Classification of matrix material

3.2 Classification Based on Type of Reinforcing Material

According to the type of reinforcing material, composites are classified in three types [24].

3.2.1 Fiber Based Composites

Fiber reinforced polymer composite systems have become increasingly important in a variety of emerging fields [36]. Fiber reinforcing materials such as cellulose, glass, carbon, basalt, and Kevlar in any composite structures enhances bulk material properties such as high mechanical strength, toughness, chemical inertness, temperature and wear resistivity [37–41].

A fiber is characterized by its length being much greater as compared to its cross-sectional dimensions. The cross-sectional dimensions of the reinforcement fiber determine its capability of contributing its properties to the composite. Fibers are very effective in improving the fracture resistance of the matrix. Fibers are divided into two groups, synthetic fibers, and natural fibers. Synthetic fibers are man-made fibers which are a result of research by scientists to enhance the properties of natural fibers. First synthetic fiber was Nylon. Fibers made from plant, animal and mineral sources are known as Natural fibers. Natural fibers are further classified according to their origin such as fruit fibers, leaf fibers, bast fibers etc. [12].

From the last few decades research has been shifting towards the use of natural fiber due to their low cost, renewable and biodegradable nature. Moreover, a new innovation introduced is to initially treat natural fibers chemically and then to embed in matrix which show improved impact toughness, stiffness and fatigue strength [42,43].

3.2.2 Particulate Composites

In particulate composites, the reinforcement is of particle nature. These reinforcing particles are of different shapes such as spherical, tetragonal, and cubic, a platelet, or any other regular or irregular shape. They enhance the strength and stiffness of the composite to some extent, also used to improve the properties of matrix materials like thermal and electrical conductivities, reduce friction, increase wear resistance, improve performance of composites at high temperatures, increase surface hardness and reduce shrinkage. The main advantage of particle reinforced composites is their low cost and ease of production [44].

Comparably fiber-based composites have shown good mechanical strength compared to particle-based composites. Particle reinforced composites have wide applications in the field where high mechanical strength is demanded with perfect wear resistance properties such as road surfaces, e.g., For road making, the solidity of cement is enhanced tremendously by addition of gravel as a reinforcing material. [45,46]. In this case the gravel acts as dispersed particles by providing stiffness and strength while cement acts as dispersion medium and binds to hold the structure together [47]. Similarly, in MMCs large quantity of Iron based delicate glassy particles are used as reinforcing material to harden the aluminum matrix. This spectacular combination of metals results in a remarkable combination of mechanical properties with high strength and plasticity in the final composite [48].

3.2.3 Laminated or Sheet Based Composites

laminated composites are also termed as sheet molding composite. it is a material in which laminated glass material is embedded in a thermoset by utilizing the common compression molding technique [49–51]. The finished material has a combination of long glass fiber embedded in unsaturated resins which provides a high mechanical strength to the composite. Laminated composites have high strength-to-weight ratio, so they are applicable in large structural components [52].

3.3 Based on the Nature of Reinforcing Material

3.3.1 Nano-Composites

The combination of two or more discrete materials at Nano scale, desired properties of material can be achieved resulting in the fabrication of an innovative novel material referred as Nano-composite. Nano-composites are generally classified as: phase separated, intercalated and exfoliated Nano-composites. These composites are prepared by using solution route intercalation of polymer, in situ polymerization, and melt processing methods [53,54].

Some very special and emerging Nano-composites are biomedical nanocomposites designed for biomedical applications viz bone tissue engineering [55], dental treatments [56], drug delivery in contagious diseases [57] and dressings of surgical sutures [58,59]. A common example of such biomedical nanocomposite is the use of black phosphorus based Nano-structure for treatment of cancer [60]. Similarly, ophthalmic properties of composite materials can also be enhanced efficiently by fixing some sort of transparent matrix material along with nanofiller for application where better optical properties are required [61]. For instance, graphene based Nano-composites due to its conductive nature have shown improved optoelectronic properties demanded for photonic applications in fiber optics [62–66].

3.3.2 Bio-Composites

Bio-composites are composite materials made from natural fiber reinforced with polymer matrix. Main advantage of bio-composites is that they are biodegradable. Demand of ecofriendly, biodegradable materials compels researchers towards bio-composites. There is so much development in bio-composites that more and more thermally stable, increased tearing strength and durability bio-composites have started to emerge. For example, bio-composite made by dispersing sugar palm fibers embedded in the starch matrix showed remarkable properties like increased thermal stability, reduction in water absorption tendency with elevated tearing strength [67–71] Tab.1.

Moving to nanoscale bio-Nano-composites fabricated have showed potential in many applications of the medical field such as fabricating scaffolds for tissue engineering and bio-packaging etc. [72–78]. Ginger fibers have antibacterial property which has been effectively utilized to sustain food packaging quality [79].

3.3.3 Bio Fibers

Today, Bio-fiber for the reinforcement of the composites has received much attention. Bio-fibers have significant advantages over synthetic fibers [80]. Many types of natural fibers have been developed for use in plastics including flax, wheat fibers, barley, oats, rye seeds, sugar cane, fibers obtained from bamboo and jute, common straw, wood, various husks, grass, pineapple leaf fiber, papyrus etc. [81].

Natural fibers gain much attention of the scientists as they are low cost with no health hazards and most importantly these bio-fibers has negligible contribution to environmental pollution. Moreover, natural fiber reinforced polymer composites will be the materials of choice as compared to common wood based structural applications. Another important type of bio fibers also add beauty to the fabricated composite is the fibers obtained from the various parts of the plants like leaves, flowers and epidermis, such bio fibers are referred as vegetable fibers [82].

3.4 Classification of Bio Fibers

The main classification of Bio fibers [83] Fig. 4.

Table 1: Chemical composition and tensile strength of polymer composites

Type	Fiber	Cellulose W/W %	Hemicellulose W/W %	Lignin W/W %	Tensile Strength (MPa)	References
GRASS	Bagasse	44,1	31,8	22,3	20–290	[84]
	Bamboo	22,8–56,7	17,2–43,8	1,1–26,6	140–230	[85]
	Canary	37,2–41,7	19–22,9	–		[86]
	Corn	41,7	26	7,4		[87]
WOOD	Soft wood	30–60	20–30	14–34	45.5–1000	[88]
	Hard wood	31–64	25–40	21–37	51–210.7	[89]
FRUIT	Coir	36–43	0,15–0,25	41–45	106–593	[90]
	Kapok	35	22	21,5		[91]
	Oil palm	47,91	19,06	24,45	100-400	[92]
STEM	Jute	61–71,5	13,6–20,4	12–13	393–800	[93]
	Flax	74,93	10,37	2,62	345–1500	[94]
	Hemp	75	15	3	550–900	[95]
	Kenaf	31-57	21,5–23	2,62	295–930	[96]
	Kudzu	33	11,3	14	130–418	[97]
	Nettle	79–83,6	6,5–12,5	3,5–4,4	650	[98]

Table 1 (continued).

Type	Fiber	Cellulose W/W %	Hemicellulose W/W %	Lignin W/W %	Tensile Strength (MPa)	References
	Ramie	61,85–73,21	5,27–7,58	4,6–9,06	220–938	[99]
	Roselle	70,20	7,21	14-91		[100]
LEAF	Abaca	60,4	20,8	12,4	400–980	[101,102]
	Banana	63–64	10–24	5	355–500	[103]
	Henequen	70–77,6	4–20	8–13,1	430–580	[104]
	Pineapple	70–82	18	5–12	170–1672	[105]
	Sisal	26	38,2	26	400–700	[106]
SEED	Cotton	82,7–92	5,6,7	0	287–597	[107]
	Kapok	64	13	23	93.3	[108]
STALK	Wheat	33–38	26–32	17–19		[109]
	Rice	28–36	23–28	12–24		[110]

4 Synthesis of Bio-Composites

Development of bio-composites involved following process:

- Preparation of fiber as filler and polymer as matrix,
- Dispersion of prepared fiber into the polymer matrix utilizing various fabrication techniques.

There are different methods that can be applied for harvesting natural fibers like mechanical processing usually good for stiff and rough fibers, chemical harvesting for soft and delicate fibers, contains property and biological degumming, e.g., for silk fibers [111] etc.

4.1 Basic Strategy

Concisely, four steps can be summarized in the development of bio-composites which include infusion, layup, amalgamation, and curing [112], Fig. 5.

Keeping in view basic strategy variety of fabrication methods have been explored for bio-composites. According to the types of reinforcement used these may be classified into two categories [113]:

(i) Particulate or small fibers

(ii) Continuous and coherent fibers

For Preparation of bio-composites reinforced with continuous fibers, initially preforms based on woven fabric extracted from natural fibers is introduced as the reinforcements. Which resulted in fabrication of laminated composite with four layers of jute and woven fabrics [114]. Before introduction into the resin matrix, the jute fabrics are chemically treated with alkali for delamination under applied stress. The final composite after curing showed a significant improvement of the mechanical properties like stiffness and toughness.

The Bio-composites fabricated from natural fibers suffers some drawbacks as compared to conventional glass fiber composites is their greater permeability and low impact strength. Research has been made to reduce or eliminate these drawbacks by pre-treatment of the fibers, engineering of new fibers or chemical

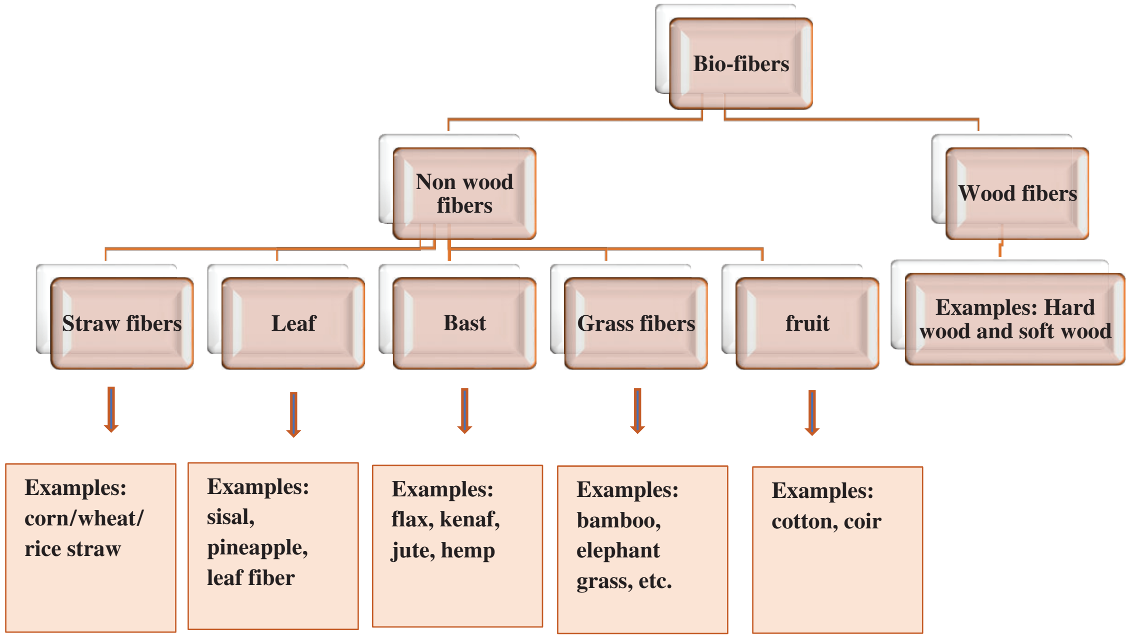

Figure 4: Classification of bio-fibers

treatment of fibers prior to impregnating with the matrix polymer. For this purpose a three-corner approach is in practice for production of bio-composites with superior/desired properties comparable to its rival, i.e., glass fiber composite. The approach utilizes bio-fiber chemical treatment, single matrix modification to a blend matrix and innovative processing for the fabrication of novel bio composites [115].

The recent trends in research proved that bio composites based on bast fiber like Kenaf, Hemp etc. proved nearly perfect mechanical and tensile properties. Similarly, bio composites made by incorporation of leaf fiber like Pineapple leaf fiber or PALF exhibit very high impact strength. Moreover, the chemical treatment of bio fibers with alkali or saline solutions have been found fruitful in reducing water absorptivity of the bio composite material. Lastly, blending of such surface treated bio-fibers with a matrix could be utilized to engineered natural/bio-fibers with demanded properties Fig. 6.

A typical example of blended filler is the fabrication of unsaturated polyester bio-composite comprising woven fabric from banana [116] and glass fibers as bifiller have been prepared. Both the fillers were distributed alternately in the polymer matrix resulting in a combined effect of properties in the final composite. Similarly, the hemp fiber reinforced composites were also fabricated using an unsaturated polyester resin embedded with needle shaped non-woven mat of hemp fibers [117]. It was revealed that the mechanical properties of Hemp fiber reinforced bio-composite were comparable to that glass fiber reinforced unsaturated polyester composites.

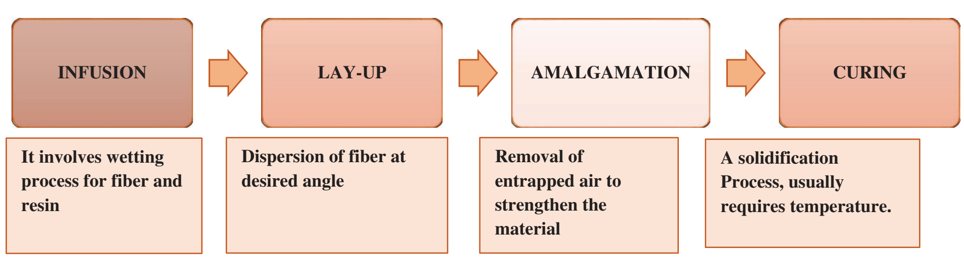

Figure 5: Developmental steps for fabrication of bio-composites

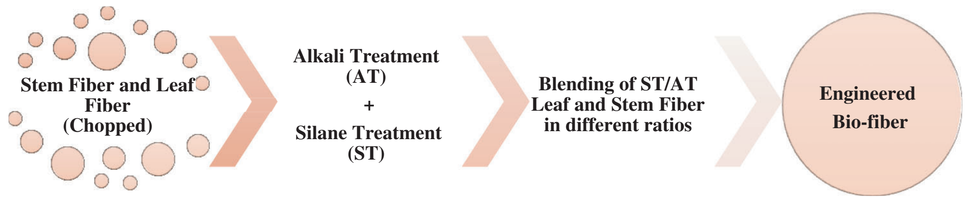

Figure 6: Scheme of engineered bio-fiber

On way to reduce the cost of bio composite is the utilization of chopped natural fiber in polypropylene (PP) matrices which also resulted in better mechanical properties in finished material [118]. These fabricated composites includes kenaf fiber reinforced PP composites using compression molding [119], Bio composites from PP and kenaf fibers by the press forming [120] and extrusion technology was also adopted to process chopped natural fibers with PP powder [121].

5 Characterization Parameters

For mechanical characterization of bio-composites several tests are performed such as stress-strain test, impact strength check, dynamic mechanical analysis (DMA), etc. The SEM, XRD, TEM, FTIR tests are conducted for the morphological and structural analysis of bio-composites. Tab. 2 shows different tests, their purpose, different mechanical set ups used with brand name, their capacity and estimated cost for the characterization and analysis of bio composites.

Table 2: Analysis tests for bio-composites characterization

Experiment	Analysis	Machine, Brands and Capacity (Cost)
Tensile Test [122]	Stress-strain relationship (young's modulus)	Universal testing machine Brands: Instron, Tinius Olsen, Zwick Capacity: 5, 15, 30, 100 KN Approx. Cost: 10–20 lakhs
Three Point Bending Test [123]	Mechanical strength, maximum load at break, mechanical modulus	
Impact Test [124]	Impact strength	Pendulum impact test machine Brands: Instron, Tinius Olsen, Zwick, WPM Leipzig, Haida Capacity: 1 J–300 J Approx. Cost: 3–10 lakhs
Brittleness [125]	Brittleness	Hardness testing machine Brands: Instron, Zwick, Buehler
Dynamic Mechanical Thermal Analysis (DMTA) [126]	Fatigue strength, glass transition temperature (tg), storage modulus	DMA analyzer Brands: Instron, NETZSCH Capacity:25N to 500N Approx. Cost: 10–25 lakhs
Thermo gravimetric Analysis (TGA) [127]	Thermal properties, onset temperature, decomposition temperature, % weight loss, chemical inertness and physical properties	Thermo gravimetric analyzer Brands: Perkin Elmer, Torbal Approx. Cost: 15–25 lakhs
Differential Scanning Calorimetry (DSC) [128,129]	Evaluating glass transition temperature of the polymers Tg, crystallization and melting point	Thermo- Modulated calorimeter
Thermal Conductivity check [130]	Insulation or conductive properties of materials	Manual results

(Continued)

Table 2 (continued).

Experiment	Analysis	Machine, Brands and Capacity (Cost)
Thermo mechanical Analyzer (TMA) [131]	Thermo mechanical stability, thermal expansion record,	Thermo mechanical analyzer Brands: Thermo Scientific LTQ, Thermo Finning
Pin-on-Disc Test [132]	Abrasion and wear properties of material	Tribometer Approx. Cost: 5–8 lakhs
Erosion Test [133]	Erosion, rusting and wear properties	Air jet erosion test rig
Fragility Test [134]	Surface corrosion, abrasion and impact damage	Manual check up
Scanning Electron Microscopy (SEM) [135,136]	Surface morphology, micrographs of fractured surface, deformation and changes in surfaces before and after finishing	Scanning electron microscope Brands: Hitachi, JEOL, ZEISS, FEI Approx. Cost: 25-150 lakhs
X-Ray Photoelectron Spectroscopy [128,129]	Molecule arrangement, strain, crystallinity and amorphous nature, composition of material	X-Ray diffractometer Brands: PAN alytical, Philips, Siemens Approx. Cost: 30-150 lakhs
FTIR [137]	Amount of component in the mixture, identification of functionalities	FTIR spectrometer Brands: Nicolet, PerkinElmer, Bruker Approx. Cost: 30–100 lakhs
CT Scan Analysis [138]	Fiber distribution in the matrix	CT Scanner Approx. Cost: 15 lakhs
Elemental Dispersive X-Ray Analysis [139]	Elemental composition of composites	Nano scanning electron microscope Brands: Hitachi, ZEISS Approx. Cost: 100 Lakhs
Transmission electron microscopy Analysis (TEM) [139]	Morphology and distribution of particle size especially in particulate composites	Transmission electron microscope Brands: CRAIC, JEOL Approx. Cost: 10 lakhs
Atomic Force Microscopy [132]	Surface morphology, surface conductivities	Atomic force microscope Brands: Veeco, RMC Approx. Cost: 20–100 lakhs
Polarized Optical Microscopy [140]	Crystallization and settling behavior	Polarized optical microscope Brands: Motic, Olympus, Nikon Approx. Cost: 5–15 lakhs
Soil Burial test [141]	Weight loss check, Biodegradability of Bio-Composite	Manual Process over time

6 Application of Bio-Composites

Bio-composites have endless applications from automotive to aerospace industries, with valuable applications in biomedical, packaging and many other industries.

Renewable bio-composites had gain very importance in engineering many of the interior and exterior parts of automobile and other automotive, shock proof and sound absorbing parts of machinery have been manufactured using these materials.

The introduction of parts made from bio composite materials have revolutionized the automobile industry by making the vehicle lighter, provided resistance to heat, improved external impact, and reduced the fuel capacity. The ground-breaking research on composites and their production at large scale by utilizing simple and low cost techniques resulted in a decline of prices with increasing demand of fabricating many other parts related to automotive sector. This led to production of mid-end and low-end cars as well [140].

Research has been carried out to explore the use of bio-composites under drastic weather condition of marine environment. As a consequence many vital goals have been achieved for marine application where better mechanical properties and biodegradability was at utmost demand. It is on behalf of these properties, the bio-composites based material have widely replaced the synthetic fiber composite material of the marine environment. Researchers have conducted many experiments on aging effect of sea water for flax/PLA bio-composites. The result showed that the absorption of sea water determined the depletion of the matrix, structural deformity, deterioration of interface between fiber and matrix, swelling behavior of composite at interfaces and total destruction of fibers due to salinity ultimately destroying the mechanical strength of the material. However, if exposed to saline environment for a much longer periods resulted in complete cracking in material. As a consequence while dealing with bio-composites for marine applications due care is needed to integrate marine structures, as these composites are biodegradable [141].

Agricultural fibers have been used into textile and paper industry for making cloth, canvas and ropes for many hundreds of years. The composites straw and mud composites have been used for construction of buildings in Egypt. Today modern industries for hemp fibers based composites are being used for making environment friendly paper and pulp. These industries are responsible for production of high-strength composite, composite panels for houses and furniture, textile and ropes, flooring carpets, heat and auditory insulation and other house hold items, etc. [142].

Kenaf fiber-reinforced composite being light weight and low cost is an alternative bio-composite material used particularly in construction [143].

7 Limitations in Preparation of Polymer Bio-Composite

Use of bio-composite material has been payed attention greatly due to their remarkable and distinct set of properties over the last few decades, but with some drawbacks such as poor processability and loss of toughness [144]. Moreover, worse dispersion issues with minimum interfacial adhesion between the fillers and the polymer matrix [145] and selection of proper solvent have limited the preparation and utilization of bio-composites.

For instance production of ecofriendly green composite demands solvents with minimum contamination effects which is very difficult to address. Solvent is the most important component of any reaction mixture which acts during the course of reaction and determines various parameters related to the processes like separation, and purification of the end products. Furthermore, solvent also plays a vital role in other steps of the production bio-composite which involve transportation of reactants and product during the various stages composite production. One solution to minimize environmental contamination by solvents is the introduction of Bio-Solvents that are prepared from renewable resources, not from fossil feedstock or by using nonvolatile solvent such as ionic solvents [146].

Besides various applications there are also some limitations for the fabrication and operation of green composites in automobile industry. For example, using cellulose-based materials as filler in thermoplastic polymers has many benefits on one hand for the environment, as these reduce CO_2 emissions in the atmosphere during their course of production, processing, and utilization. While on the other hand incorporating such biodegradable materials in thermoplastic polymers faced many challenges including: (1) the compatibility issue between hydrophilic nature of cellulose and hydrophobic organic polymers, (2) moisture absorptivity issues due to hydrophilic nature, (3) improper dispersion and high risk of agglomeration, and (4) poor heat resistance. All these factors limits the use and production of bio-composite materials when compared to glass fiber based composites [147].

However, research never ends here, the introduction of promoters for adhesion, chemical modification of the filler have helped in incapacitating many of these limitations. The efforts to overcome these complications are going on worldwide [148].

8 Future Potentials

The demand for supplies of bio-composites is growing in the world from year to year. This growth in Europe is estimated at 32% per annum, from 0.3 million tons in 2011 to 1.2 million tons in 2016. Higher growth is expected in Asia, i.e., 41% per annum, reaching production capacity ca. 1.1 million tons in 2016. Also, biodegradable plastics, especially PLA and PHA, have demonstrated impressive growth rates which will increase by 2/3 by 2016, reaching an estimated 298,000 and 142,000 tons, respectively [149].

Selection of suitable material as a matrix like metal, polymers and ceramics, and fillers of nanosized bio-composite material could have endless applications in industrial and engineering fields. These bio-materials are being used and produced according to the growing need of the society to obtain optimum strength [150].

The production of Green composites is increasing day by day due to the growing demand of consumers, that reduces the use of artificial material, higher stability, biodegradability and bio-compatibility, ecofriendly nature, and potentially recyclable, etc. [151].

Pin near future, ecofriendly green composites could be developed at much reasonable cost with much more demanding mechanical properties which will help to maintain a balance between ecology, economy, and technology. They are successfully replacing the petrochemical composites which will eventually result in consumer benefit. Consequent development in the field of green composite can be seen in the domain of green composite in the past years [152].

The building industry is using more than 35% of global final energy, nearly 40% of energy-related CO_2 emissions [153], and almost 45% of global resource consumption. The demand for resources will rise exponentially as the global population will increase from six billion to nearly nine billion by 2040 [154]. Construction of more housing units for growing global population in a synchronized rate of this population growth will be a challenge. An exemplary estimate for one developed country like Germany alone, it is estimated need for between 350,000–400,000 new housing units to be built per annum [153]. Concrete and aggregate materials are the predominant building materials of the modern day, which along with high-strength materials like steel and aluminum are responsible for the largest share in air pollution by adding a good share to greenhouse gas emitted from the building industries. If the same type of building materials with similar rate of production is used to meet these demand, it will lead to severe environmental hazards [154].

So, now it has become very essential to work for production of renewable and biodegradable building materials which could be applied in wider applications with more innovative methods in architecture. One of such innovative approaches in this area is the utilization of natural fiber-reinforced polymers, which are also called bio-composites, and are filled with annually renewable lignocellulosic fiber. These fiber-reinforced polymer materials are not only renewable but can induce lightness, which will ultimately reduce the need for concrete and metals in construction and finally will play a greater role in reduction of environmental hazards related to greenhouse gas [152].

Nowadays, the use of bio-composites in biomedical applications offers several advantageous characteristics. Bio-composites are now used to repair, reconstruct, and replace human hard tissues.

Against fatigue failure these composites provide high fracture toughness and high resistance. Also, these bio-composites are highly compatible with modern diagnostic methods, such as computed tomography (CT) and magnetic resonance imaging (MRI). Biopolymers offers better aesthetic characteristics in dental implants. In clinical applications bio-composites are used in cages for spinal fusion. Benefits for patients are faster bone healing, no risk of pathogen transfer compared to allograft, faster and cheaper surgery and less pain compared to autograph [153].

There is a growing trend to use Biofibers (as fillers and/or reinforcement) in plastic composites. Their properties (high specific stiffness, flexibility during processing, and low cost) make them attractive to manufacturers. These composites are predestined to find more and more applications in the near future. New markets will develop when natural fiber composite products become more durable, dimensionally stable, moisture-proof, and fire-resistant [154].

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