Chapter

# Eco-Friendly and Biodegradable Green Composites

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## Abstract

Natural fibers, are environmental friendly, biodegradable, abundantl, renewable and cheap with low density. Plant fibers are light compared to glass, carbon and aramid fibers. The biodegradability of plant fibers contribute to a healthy ecosystem while their low cost and high performance fulfills the economic interest. The effect of fiber content on the properties of natural fiber reinforced composites is particularly significance. Important factor that significantly influences the properties and interfacial characteristics of the composites is the processing parameters used. Biocomposites offers a significant market in automotive and decking market but application in other sectors has been limited. Green composites are promising because they are renewable, biodegradable and sustainable for non-renewable composites.

**Keywords:** biocomposite, biodegradable, eco-friendly, sustainable, fibers

## 1. Introduction

Globalization and sustainability has made life not only feasible but challenging too. Materials which are obtained from resources that are renewable tend to be suitable for sustainable development. These materials have a global value since they can act as a counter to the various environmental issues such as waste management problems, increase in global warming, the constant rise in oil prices and the deteriorating fossil resources. Different varieties of renewable materials have been used for many years across the food, furniture, and textile industry such as vegetable oils, starch and cellulosic based polymers, cotton, natural fibers, silk, and wool [1]. On the other hand, it is only recently that these materials have gained interest as a potential alternative to synthetic based polymers for different kinds of industrial applications like automotive, films, construction, paper coating, packaging and biomedical applications. The synthetic polymers pose many drawbacks towards the environment in ways such as the amount of vapors and toxic gases released after incineration and improper disposal, there has been more research work being focused on new green biopolymeric materials and their effective utilization in green composite applications.

Over the years, bioproducts have gained commercial importance. Chemical processes such as production of 'green' ethylene through dehydration of ethanol and further production of 'green' polyethylene, polyvinyl chloride and some other plastics have been reviewed. Certain technological developments have also been used to enhance certain material properties of polymers that are bio-based; an example of which is development of heat resistant polylactic acid, thereby allowing extensive applications. Bio-fibers with stable properties are being produced over time by optimizing plants. There have been numerous applications occurring lately such as packaging, biomedical products, textile, agriculture, construction where these biodegradable biopolymers and biocomposites are an appropriate sustainable replacement [1, 2].

Biospecific and biosimulation materials cover the whole field of biofunctional materials. Biofunctional materials are synthesized from the view point of functionality design. The functionality design is based on determination of the polymer structure that realizes the desired functionality and property of materials, and on exploration of the appropriate method of polymer synthesis, polymer reaction, and polymer modification that yields the designed polymer structure.

### 1.1 Concept of composites

A composite is a structural material which includes a combination of different entities that are insoluble in each other and are mixed together at a macroscopic level [1]. One of the constituents is known as the reinforcing phase and the other one into which the reinforcing phase is embedded is called the matrix (**Figure 1**). The reinforcing phase materials are found to be made of varying textures that can be in the form of flakes, fibers or particles [2]. On the other hand, the matrix phase materials are generally made of continuous phases [3, 4]. One of the most common examples of naturally found composites includes wood (cellulose fibers are reinforced into lignin matrix) and bones (reinforcements of bone-salt plates consisting of phosphate and calcium ions are added to the soft collagen matrix). Each constituent of the composite has different roles giving rise to a strong structural material. The matrix component within composite materials gives a defined shape, protects the reinforcements from environmental damage, transfers loads to reinforcing phase and improves the toughness of material [5]. The reinforcements in composites get strength from the matrix, stiffness and other mechanical properties; contain a high thermal expansion coefficient, high conductivity and good thermal transport [6].

### 1.2 Pros and cons of composites materials

#### *1.2.1 Pros of composites*

Composite materials have various advantages that can be used for different applications. Composite materials are very lightweight and have a low density

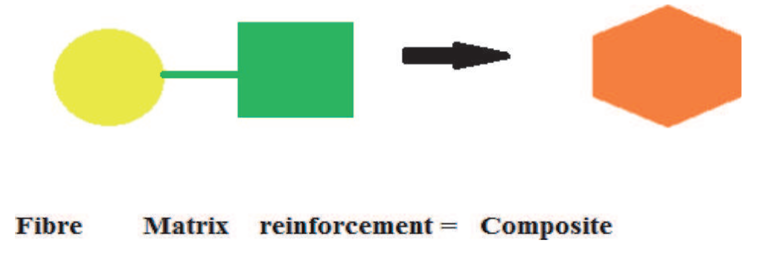


**Figure 1.**
*Concept of biocomposite.*

making it easier to mold into complex forms and modules like Modular construction. These materials have a high specific stiffness, creep resistance and strength with an improved friction and wear properties. Composites have low thermal expansion and electrical conductivity giving rise to good dumping properties and good fatigue resistance. These composite materials are easily bondable, have lower radar visibility and have the capability to store and release internal energy, leading to a lower overall system cost. Composite products are known to have excellent heat sink properties. The mechanical properties such as strength-weight ratio, stiffness-weight ratio and fatigue properties of the composite products are better than most of the common engineering metals like steel or aluminum. With improved corrosion resistance and a high resistance to impact damage, the composites have indefinite shelf life just like metals. Composites can be used to obtain a varied combination of properties which cannot be attained in other materials such as polymers, ceramics or metals alone. One of the major advantages of composites is the ability to incorporate sensors into the matrix which can be used to monitor and correct the material performance, giving rise to a range of applications towards Smart composites (**Table 1**).

### *1.2.2 Limitations of composites*

Though composite materials possess a huge number of advantages, there are certain limitations to the same. The composite materials are known to have a low ductility and have certain temperature limits. Due to the presence of more than one component, the material can be subjected to solvent or moister attack. The matrix component of the composite is generally weak giving rise to low toughness, higher brittleness, higher susceptibility to damage and weak transverse properties. The

| The properties of bio composites | Characteristics | | |
|---|---|---|---|
| | **Mechanical** | **Physical** | **Chemical/ Biological** |
| Intrinsic properties (based on chemical composition) | Flow limit<br>Tensile/ compression resistance<br>Poisson ratio<br>Electricity modulus | Density<br>Form and geometry<br>Color esthetics | Flow limit<br>Tensile/ compression resistance<br>Poisson ratio<br>Electricity modulus |
| Behaviour | Breaking strength<br>Fatigue resistance<br>Crack resistance<br>Rigidity<br>Wear resistance<br>Shock resistance | Coefficient of thermal expansion<br>Electrical conductivity<br>Refractive index | Biofunctionality<br>Bioinert<br>Bioactive<br>Biostability<br>Biodegradation |
| Surface properties | Bending modulus<br>Hardness<br>Shearing modulus<br>Bending resistance<br>Shearing resistance | Surface topology<br>Texture<br>Roughness<br>Hardness<br>Coefficient of friction | Adhesion |
| Processing | Reproducibility, can be sterilized, Packaging feature | | |

**Table 1.**
*Biocomposite properties different categories.*

composite materials are difficult to attach onto other materials, requiring the need of additional materials such as fasteners. Repairing composites can introduce many other problems, making the disposal and reuse of composites very difficult. Composites have a limited shelf-life discouraging its usage for long term applications. Composite materials have a very complicated manufacturing and fabrication process requiring sophisticated tools and high cost raw materials. Composite materials require refrigerated transport and storage. In most of the cases, hot curing is necessary which takes time and requires special tools; overall adding to the high expense of producing composite materials.

### 1.3 Difference between smart and composite material

Though smart materials and composite materials sound similar, they are fundamentally different. Smart materials have a minimum dual function whereas composite materials consist of dual or more components/phases (thereby being called hybrid materials).

Smart materials serve various functions within one product, some common instances of which include actuator/sensor ability in addition to having form, having the ability to bear structural weight without breaking. The classic example having huge industrial value is Nitinol, an alloy of Nickel-Titanium. This material can be mechanically deformed like bent and can be returned to the pre-deformed shape by heating the material. Another good example of a smart material will be Lead-Zirconate-Titanate (PZT) which is a ceramic that mechanically deforms when an electrical potential is generated. PZT alloy has found an actuator application because a reverse potential produces expansion of the material geometrically (**Figure 2**).

As mentioned previously, composites consist of many different materials in two or more phases, which allow us to specifically engineer the composites to produce desired properties like enhancing mechanical stress, conductivity, etc. The

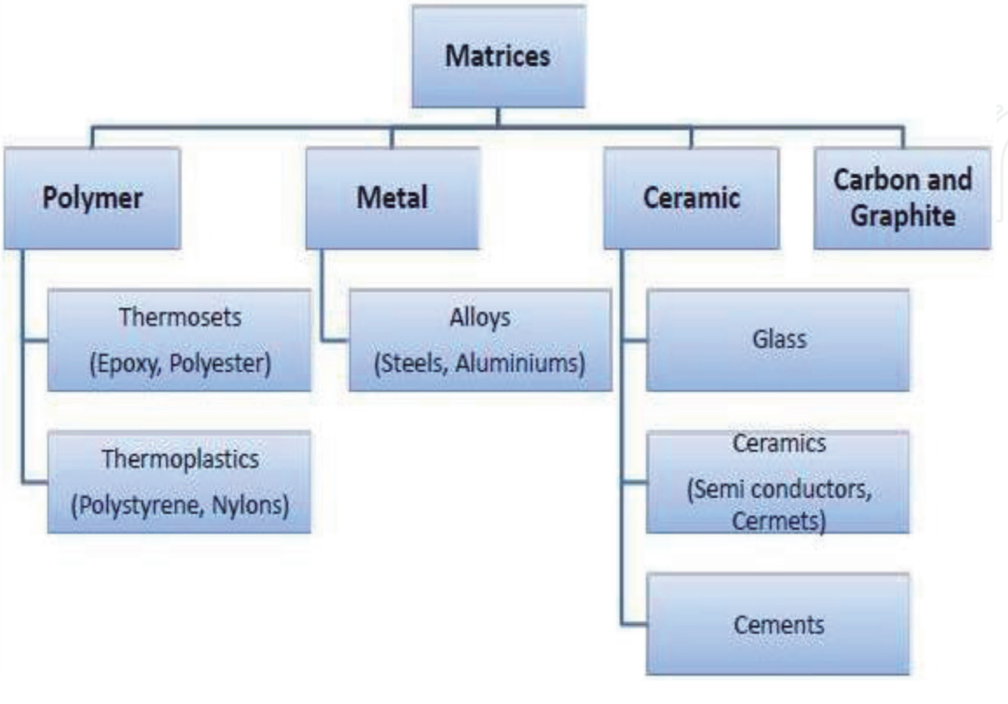


**Figure 2.**
*Classification of composite materials with respect to matrices.*

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compound will be considered a composite material as long as the base materials retain their physical morphology and characteristics.

### 1.4 Applications of biocomposites

| | |
|---|---|
| Electrical, Electronics | • Antennas<br>• Cable tracks, Windmills<br>• Insulation for electrical construction<br>• Circuit breakers, Printed circuits<br>• Armors, boxes<br>• Television towers - Top |
| Buildings and Public Works | • Facade panels<br>• Covers (domes, windows)<br>• Chimneys<br>• Profiles, Partitions<br>• Swimming pool<br>• Concrete molds |
| Road and Rail Transports | • Casings, cabins<br>• Panels<br>• Isothermal trucks<br>• Body components<br>• Power units, wagons, doors, seats<br>• Bottles for gas<br>• Wheels, grills<br>• Ventilation housings<br>• Chassis, Suspension<br>• Highway tankers<br>• Shafts and suspension springs<br>• Trailers |
| Marine and Cable Transports | • Boats: Pleasure and racing canoes<br>• Crafts, Patrol boats, Trawlers<br>• Cabins: Telecabins, Telepherique<br>• Anti-mine ships, Landing gears |
| Air and Space Transports | • Rocket boosters<br>• Shields<br>• Passenger aircrafts and Gliders<br>• Reservoirs, Nozzles<br>• Blades, Propellers<br>• Shafts and Brake discs<br>• Aircraft components: radomes, ailerons, stabilizers |
| Mechanical applications | • Weaving machine rods<br>• Compressed gas bottles, Tubes for offshore platforms<br>• Gears, Bearings, Casings<br>• Pneumatics for radial frames<br>• Jack body, Robot arms, Flywheels<br>• Pipes, Components of drawing table |
| Sports and Recreation | • Skates, Bows and arrows<br>• Rackets, Fishing poles<br>• Javelins, Helmets<br>• Skis, Poles used in jumping<br>• Sails, Surf boards |

## 2. Constituents of composites

Biocomposite materials are a hybrid of a reinforcement material made of natural fibers (plants or from cellulose derivatives) and a matrix material (resin). The resin is generally a polymer matrix made of either renewable or non-renewable resources. The natural fibers, also called biofibres, can be made from wood fibers (softwood and hardwood) or from non-wood fibers (hemp, wheat, flax, jute, sisal, kenaf, etc).

### 2.1 Classification of composites materials

The classification of composite materials can be done into different classes based on the phases:

- One of the most commonly used classifications is based on the material of the matrix. The major classes include Organic Matrix Composites (OMCs), Ceramic Matrix Composites (CMCs) and Metal Matrix Composites (MMCs).

- The class Organic Matrix Composite is a more general term which includes subclasses, including Carbon matrix composites or carbon–carbon composites and Polymer Matrix Composites (PMCs).

Another commonly used classification is based on the material of the reinforcement used. The classes are namely fiber reinforced composites, particulate composites, and structural composites.

- Fiber Reinforced Composites, as the name suggests, are made from fibers that are embedded into the matrix material. The Fiber Reinforced composites (FRP) can be further classified into 2 types - Short-fiber reinforced composites (those containing discontinuous fibers) and Long-fiber reinforced composites (those with continuous fibers). A fiber composite can be called a discontinuous one when the properties of the material vary according to the fiber length. On the other hand, the composite can be called continuous fiber if further increase in the fiber length has zero effect on the elastic modulus of the composite. The fiber particles are small in diameter. Although these fibers tend to have really good tensile properties, they can be bent easily when pushed axially. Hence, to prevent buckling and bending of the individual fibers, they must be constantly supported externally.

- Structural Composites consist of different layers of material with different orientations, held intact because of the matrix. Sandwich structures and Laminates are important examples in this category.

- Particulate Composites are made of a dispersed phase, which is in the form of particles, embedded in a matrix body. The dispersed phase particles may have preferred orientation (flakes) or have random orientation (powder form). Some examples that fall under this category include concrete and wood particle boards.

### 2.2 Types of polymer based matrix

The major functions of polymer based matrices in biocomposites are to permit the transference of tension between fibers, to prevent mechanical abrasion of surface fibers and to act as an effective barrier against hostile environments. The structural composites' tensile load carrying capacity is influenced by the function of the matrix. Key component of the biocomposite is the matrix or binding agent. Polymer, metallic, ceramic, and carbon are the various kinds of matrices generally used. Presently, polymer based matrices are highly utilized in industrial applications and these polymer resins are available in two kinds [6]:

a. Thermosetting: Upon heating application, the thermoset being a firm and inflexible cross linked component does not get molded [7]. They are pretty rigid and non-elastic in nature unlike elastomers and thermoplastics. Natural fiber composites use different kinds of polymers as matrices. Epoxy based resins such as fiberglass, phenols, polyamides, acids etc., are the frequently used thermoset polymers [3]. Due to their unique properties and their use in various applications, unsaturated polyesters are most preferred to be used as a matrix in a biocomposite. Owing to the polymer benefits such as room temperature curing property, decent mechanical characteristics, and clearness, they are manufactured more industrially in comparison to thermoplastic based resins. Studies have stated about cellulose fibers being reinforced with polyesters [8]. Few other systems which have similar potential are polyesters combined with pineapple leaf fibers, sisal, jute, coir, straw etc. [4].

b. Thermoplastics: These polymers tend to mold when heat is applied and can regain their shape after cooling. Their properties do not get affected even if they are reheated and reshaped numerous times. Polymethacrylate, high density polyethylene, polyvinyl chloride, low density polyethylene, polystyrene etc. remain the commonly used thermoplastics as matrix in biocomposites.

The kinds of thermoplastics that can be utilized for biocomposites are the ones whose processing temperature does not exceed above 230°C such as polyolefins, polypropylene, and polyethylene. Some of the technical based thermoplastics which need temperature > 250°C for processing cannot be utilized for creating biocomposites. The fibers have to be degraded initially for further use. Examples: polyesters, polyamides, and polycarbonates.

## 3. Natural fibers reinforced composite

Reinforced phase plays a very important role in determining the overall properties of the composite. Natural fibers can be broadly classified into 3 categories: Plant - based fibers, Animal - based fibers, Mineral - based fibers. One of the commonly used reinforcements is the mineral - based fibers, including carbon, fiberglass and Aramid [9].

### 3.1 Carbon fibers

Carbon fibers are unidirectional reinforcements. Due to this unique structural property of Carbon fibers, they can be structured in a way wherein the composite is stronger in a particular direction making it easier for the composite to bear heavy loads. The physical properties of carbon fiber can be modified by controlling different parameters such as the alignment of fiber, nature of the matrix, fiber-matrix volume fraction and the molding conditions.

### 3.2 Glass fibers

Glass is known to be extensively used as reinforcement in most of the polymeric matrix composites (PMCs). The main advantages observed during usage of glass fibers include low cost of production, good chemical resistance, high tensile strength, and excellent insulating properties.

### 3.3 Kevlar fibers

Kevlar fibers are known to belong to highly crystalline aramid (aromatic amide) fibers. These fibers have a very high ratio of tensile strength to weight and the lowest specific gravity among the currently used reinforcing fibers. Due to their superior mechanical properties, they tend to find major applications in marine and aerospace industries.

### 3.4 Boron fibers

Boron fibers are especially known for having extremely high tensile modulus. Another prominent feature of these fibers is the buckling resistance that results in a high compressive strength for boron fiber reinforced composites (**Figures 3** and **4**).

Though the present composite industry majorly depends on synthetic reinforcement fibers, the use of natural fibers have been gaining attention in recent years for academic as well as industrial purposes. In the present time, many different plant-based natural fibers have been explored and researched upon to identify unique properties. Some of these are used in plastics as an reinforcement; some examples of which include hemp, kapok, jute straw, paper mulberry, oil palm empty fruit bunch, wood, wheat, barley, kenaf, rye, rice husk, cane (sugar and bamboo), flax, reeds, oats, sisal, grass, coir, pennywort, water hyacinth, raphia, ramie, pineapple leaf fiber, banana fiber and papyrus [5].

One of the on-demand natural fiber reinforced composite is the thermoplastic matrix containing reinforcements made of special wood fillers due to them being light in weight, possessing reasonable stiffness and strength. Natural fibers have shown immense potential to be used in replacement to non-renewable materials due to their low cost, promising thermoplastic properties, minimal to zero health hazards and can act as a solution for environmental pollution [10, 12]. Some plant proteins have also been used as reinforcements. One such example is the wheat gluten, which when plasticized have a unique ability to form a strong cohesive

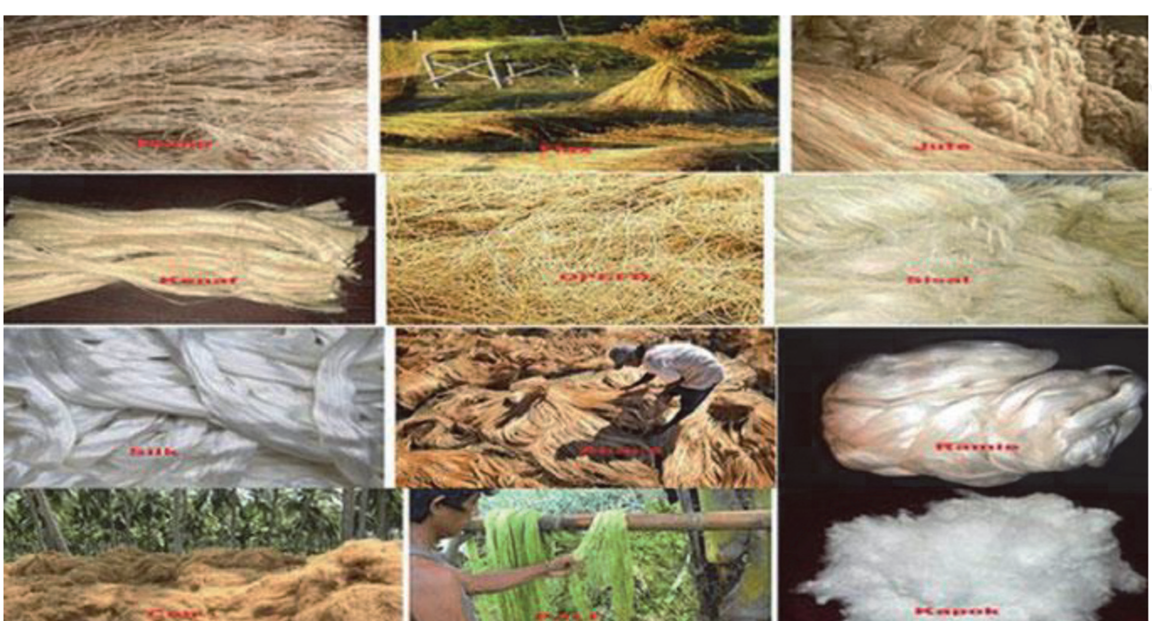



**Figure 3.**
*Different types of natural fibers used as reinforcement in polymer composites.*

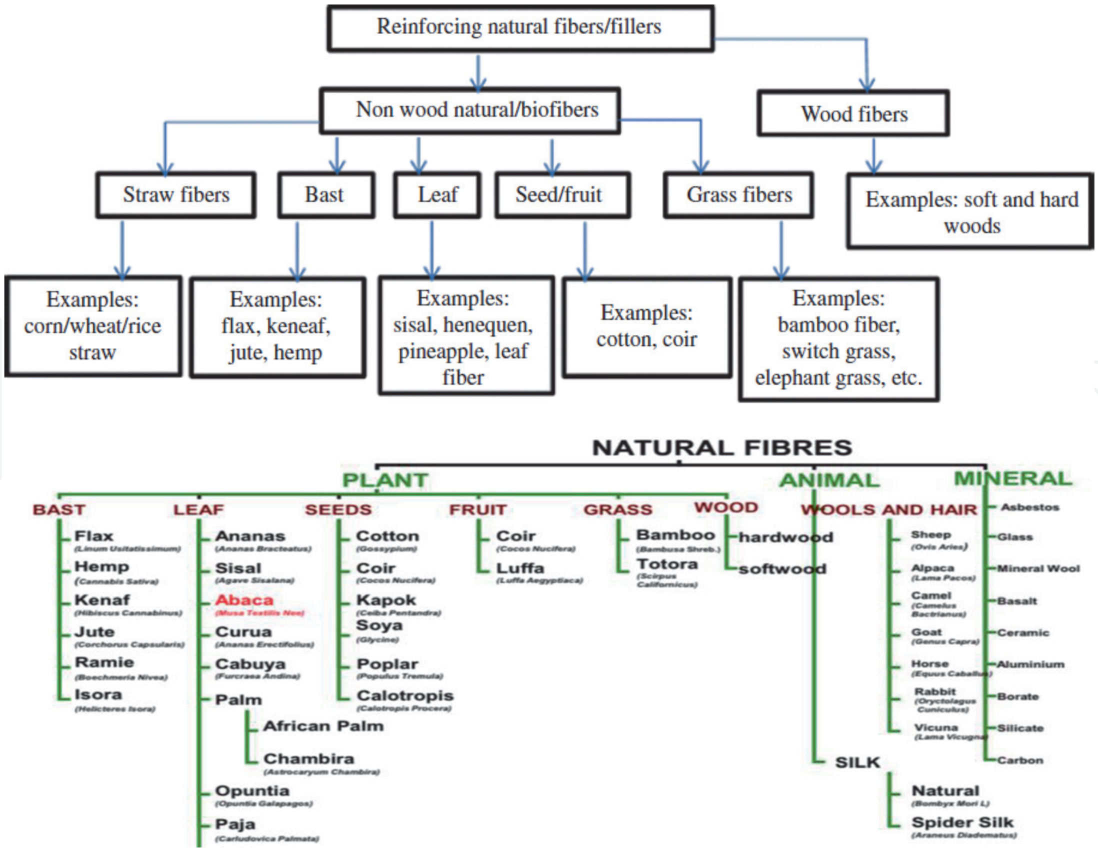



**Figure 4.**
*Classification of various fibers of different origin and types with examples [10, 11].*

blend with high viscoelastic properties [13–15]. Due to these distinctive properties, wheat gluten has been tremendously used in the making of packaging materials and edible biodegradable films.

Composites based on biologically degradable polyester amide and different plant fibers like flax and cottons, have been investigated thoroughly. These composites generally possess good mechanical properties, such as high biodegradability and good water resistance. Kenaf is a biodegradable and environmentally friendly crop belonging to the hibiscus family (*Hibiscus cannabinus* L). In a particular research work, Aziz et al. manufactured composite made of a polyester resin reinforced with Kenaf fiber and further studied the mechanical properties of the composite. The properties displayed by the composite were highly satisfactory and fiber could be blownto a height of at least 10 meter. By looking at the present research scenario, natural fiber reinforced polymer composites have the capability to act as a substitute for scarce wood and wood based materials that have many structural applications in the future [16] (**Figures 3** and **4**).

Plant - based fibers, also called vegetable fibers, are classified into different types based on their origin [17]. The characteristics of plant fibers majorly depend on certain factors such as the type of plant used, the area where it is grown, the plant's botanical age, and the protocol of extraction used. One such example is coir which is known to be a tough and hard fiber with multicellular layers, with the central portion called as "lacuna". Another familiar example is Sisal leaf fibers which are observed to have a high mechanical strength. Pineapple leaf fiber extracts are soft and are rich in cellulose. Oil palm fibers, having a similar cellular structure to coir, are hard and tough. Cellulose molecules make the major constituents in most of these plant fibers. The hydroxyls groups present in the basic unit of cellulose have the ability to form intra-molecular hydrogen bonds where the bonding is within the macromolecule, or intermolecular hydrogen bonding between two different cellulose macromolecules and or form hydrogen bonds with hydroxyl groups present in the atmosphere [18, 19]. It can be observed that all plant fibers have a high hydrophilicity, with their amount of retained moisture reaching about 8–13% [20]. Though cellulose is present in a huge quantity inside a plant, they also contain other natural substances such as lignin. The major role of lignin is to act as a cementing or bonding material between the cells of plant fibers. The content of lignin fibers influences a plant's structure, its morphology and its properties.

An important property of vegetable fiber influencing its reinforcement properties is the degree of polymerization (DP). The fibers differ drastically from each other due to the presence of cellulose molecules with differing DPs. Most of these fibers generally consist of a mixture of a base polymer homolog with the configuration $(C_6H_{10}O_5)_n$. The plant fiber known to illustrate the highest DP among other plant fibers is Bast fibers, with values nearing 10,000. In the olden times, these fibers found tremendous applications as packaging materials such as gunny bags and sacks, for making ropes, as a geo-textile material, for making twines and cords, and as carpet-backing [21, 22]. The most common bast fiber found in Cannabis sativa plants is Hemp, which is a lingo cellulosic fiber, repeatedly used as reinforcement in biodegradable composites. It is used in the making of various items such as shoes, toys and clothing, due to its non-toxicity, biodegradability and its ease for recycling [23].

### 3.5 Advantages of natural fiber reinforced composite

As mentioned earlier, natural fibers being used as reinforcement in composite materials tend to display good mechanical properties, thereby gaining a lot of attention in recent years. They are known to be fully biodegradable, renewable, environmentally friendly, cheap, available in abundance and have a low density [24]. Plant fibers are observed to be considerably light in weight when compared with mineral-based fibers. Due to their organic origins, plant fibers tend to possess high biodegradability which contributes to maintaining a healthy balance in the ecosystem. Due to the considerable low cost and high performance, these fibers can be termed as economically superior to other counterparts and can find huge applications in the industries. When natural fiber-reinforced plastics are combusted at the end of their life cycle, the amount of CO2 released from the combustion process is equal in amount assimilated during their growth [25]. Plant fibers have very low abrasivity which makes the recycling process of the composite materials much easier. Plastics reinforced with natural fibers, when used along with biodegradable polymers as matrix material, are considered to be the most environmentally friendly compounds because of their ability to be completely decomposed at the end of their life cycle [26, 27]. Natural fiber composites are used as a substitute to glass in non-structural applications. One such example is the automotive components that were initially manufactured with glass are now replaced with natural fiber reinforced composites [11]. Most of the plant fibers, when used in the unmodified form inside a composite, tend to produce unsatisfactory mechanical characteristics. To avoid this problem, the surface of plant fibers are treated with certain chemicals or compatibilizing agents prior to the fabrication of composite. The properties of these plant fibers can be further improved either by physical treatments such as corona treatment and cold plasma treatment, or by chemical treatments using peroxide, sodium hydroxide permanganate, isocyanates and maleic anhydride organosilanes [28]. In terms of mechanical properties of natural fibers, the values are quite low when compared to glass fibers or other mineral based fibers. When it comes to specific properties, especially stiffness, natural fibers values are near to those of glass fibers [29, 30]. Natural fibers have shown high tensile strength and stiffness values. Tensile strength within composites are majorly governed by the reinforcement used. Hence, natural fibers along with matrices can prove to produce the desired mechanical properties needed for the specific application [6, 9].

### 3.6 Disadvantages of natural fiber composites

Biocomposites function and quality majorly relies on biofibre characteristics. On the other hand, when biofibres are used for applications related to building materials, the composites have shown some disadvantages such as possessing high moisture absorption, low modulus elasticity, faster decomposition when surrounded by basic conditions, during microbial encounter, and visible variability in mechanical characteristics. In order to overcome these limitations, natural fibers need to be thoroughly studied to produce better performing fibers in future. Even though biofibers have various advantages for their usage in composites, they do possess certain disadvantages like being incompatible with other matrices, reduced wettability etc. [31, 32]. As mentioned briefly, the physical and chemical characteristics of biofibres are determined by cell wall based polymers and their matrix component (**Table 2**). The major properties of the fibers such as flammability, dimensional stability and biodegradability can be directly altered using external factors such as acids, bases, and UV rays by converting the green composite into carbon dioxide and water [30]. Therefore, to effectively overcome these limitations, there is a requirement to improve biofibre properties through altering the cell wall polymers chemistry [28].

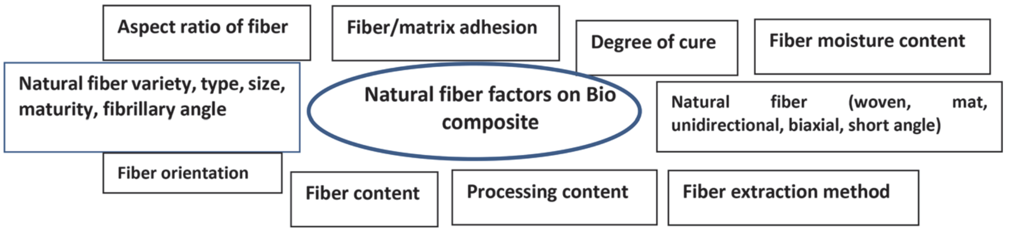
In general, for achieving a decent function of short fiber reinforced polymer composites (SFRP), the content of fiber in the composite should be considerably higher [4]. The tensile characteristics of fiber reinforced is usually affected by occurrence of fiber and other materials used in the matrix [3]. Therefore, researchers are heavily focussed on studying the biofibers used in biocomposites and how they affect it [4].

| Fiber | Density ($g/cm^3$) | Elongation (%) | Tensile Strength (MPa) | Elastic Modulus (GPa) |
|---|---|---|---|---|
| Hemp | 1.47 | 2–4 | 550–1110 | 70 |
| Banana | 1.2 | 1.8 | 400 | 13–24 |
| Ramie | 1.47 | 3.6–3.8 | 400–938 | 61.4–128 |
| Flax | 1.4 | 2.7–3.2 | 500–1500 | 27.6 |
| Kenaf | 1.45 | 1.6 | 930 | 53 |
| Jute | 1.4 | 1.5–1.8 | 393–773 | 10–55 |
| Sisal | 1.3–1.5 | 2.0–2.5 | 511–635 | 9.4–22 |
| Coir | 1.2 | 30 | 287–800 | 4.0–6.0 |
| Kraft | 1.5 | 4.4 | 1000 | 40 |
| Cotton | 1.5–1.6 | 7.0–8.0 | 287–800 | 5.5–12.6 |
| Bamboo | 1.41 | 3.5 | 593 | 18–26 |
| Kapok | 1.69 | 0.7 | 100–1500 | 3–5 |
| Phormium | 1.2–1.4 | 0.9 | 250–310 | 26.5 |
| Pine apple | 1.1–1.3 | 1.2 | 188–308 | 11 |
| Bagasse | 1.2–1.3 | 1.3 | 300–350 | 12 |

**Table 2.**
*Properties of selected natural and manmade fibers [6, 8, 9].*

Natural fibers are generally known to be hydrophilic in nature and the polymer matrix tends to be more on the hydrophobic side. Due to this difference in their polarity, the composite material usually inclines to aggregate. There is increased water absorption as a result of hydrophilic fibers, showing a weak resistance to moisture. This further leads to producing poor tensile property reinforced composites. In addition to the basic cellulose unit, fiber surfaces contain wax coating and non-cellulosic compounds like lignin, pectin, and hemi-cellulose resulting in weak bonding among the biofibers and matrix.

Hydrophilicity being an undesirable property for obtaining natural fiber reinforced composite having good tensile properties, the fiber's hydrophobicity needs to be increased by using surface modifications (surface treatment). The natural fibers are modified for enhancing hydrophobic nature, roughness, interface bonding among the biofibres and matrix, and wettability. The modifications of the fiber also decrease the moisture absorption of the composite which gives us enhanced tensile properties [10, 12, 16, 17, 23].




## 4. Applications of biodegradable polymers

i. Food Industry

The two main areas having applications in this sector are food packaging and edible films. The aim of food packaging is to enhance shelf life, ensure food safety, minimize food losses, improves the organoleptic properties of food like appearance, odor, and flavor. To replace the synthetic polymers, starch based biodegradable polymers could be utilized as an effective alternative with better properties. Although, the constituents involved in synthetic starch based packaging materials aren't fully inert. There is a possibility of migration of toxic substances into the food product which can affect humans. Due to this problem, alternative packaging materials are being studied [29, 32]. For example, investigations have led to the formation of starch or clay based nanocomposites that have shown low movement of polymeric substances, enhanced mechanical properties that can be utilized as a food packaging material. The characteristics of biodegradable films are colorless, flavorless, odorless, non-poisonous, and ecological. In low humidity conditions, these films exhibit very little penetrability to oxygen and help in increasing shelf life and quality of food product without compromising consumer acceptability. The compressed films or trays can be easily degraded by microbes as they readily dissolve in water medium. Therefore, starch based biodegradable polymers are of potential interest for food industry applications.

ii. Agriculture

In this sector, the key applications of biocomposites are greenhouse covering, mulch film, and fertilizer controlled release materials. Agricultural films are mainly consumed. Traditional films are disposed of by landfill, recycling or incineration. These processes take a lot of time, are not cost effective and pollute the environment. The important factor in developing agriculture productions is the effective usage efficiency of fertilizers. But, the fertilizers tend to escape to the environment because of surface runoff, leaching and vaporization thereby causing economic disadvantages and environmental issues. Starch based biodegradable polymers come into the picture to overcome these limitations [2]. The biocomposite can be utilized as a fertilizer controlled release matrix to release the fertilizer in the desired way. The films can be disposed of later after plowed into the soil. Due to their use, toxic residue formation does not take place after degradation. More studies are being explored involving starch based films in this sector. For instance, bio-nanocomposites are created by merging starch based film with additives like titanium dioxide, silicate or MMT to enhance mechanical characteristics.

iii. Medical industry

Starch based biocomposites can be utilized as an effective raw material due to their benefits such as biodegradability, biocompatibility, non-toxic, decent mechanical properties and degradation as needed.

Their usage in bone tissue engineering has been studied [22]. Structural framework support and degradation from the area of application is fastly offered by starch based biodegradable bone cements. Due to binning with bioactive particles, bone growth occurs at the bone cement interface and some amount resides because of polymer degradation. Bone tissue engineering scaffold involves the usage of these polymers. In drug delivery applications, starch based biopolymers are used. After drug depletion, this device does not have to be removed surgically. The starch based hydrogels or microspheres are used in different biomedical applications because of their novel properties like hydrophilicity, penetrability, biodegradability that mimics biological structures to some extent. Starch based biocomposites are of particular interest when it comes to biomedical applications [7, 11, 17].

### 4.1 A shift towards greener future

There is a lot of progress happening in the current field of research and development. Due to extensive usage of petroleum products, petroleum resources are getting exhausted and this also affects the environment and water bodies due to accumulation of plastics [7]. This is a huge concern as it affects the survival of human beings and animals. Because of these limited petroleum based resources, there is an urgent need to switch over to produce biodegradable alternatives. Biodegradable plastics are being produced to replace the synthetic polymers due to excessive usage of non-renewable polymer resources. Plants and crops can be used as suitable resources that can effectively replace the existing petroleum based products [11]. Biocomposites which are biopolymers reinforced with natural or biofibers can be utilized instead of synthetic composites such as glass fiber. Scientists are eyeing different approaches by merging biofibers like sisal, hemp, flax etc. with polymer matrix to produce biocomposites [11].

Composites are anisotropic in nature according to their structure. A matrix component (resin) is usually mixed with natural fibers obtained from plant based sources or cellulose to form biocomposites. Wood based fibers and non-wood fibers such as hardwood, softwood, jute, kenaf etc. are used as biofibres. The biocomposite's main constituent is the biofiber and it is obtained from tree, plant, or shrub sources [3]. The structure of biocomposites looks and functions similarly to living materials during the process and also enhances the strength properties of the matrix being used, thereby providing biocompatibility, for instance in forming scaffolds in bone tissue engineering. Structure and service environment are two important factors that determine the biodegradability rate in biopolymers. Natural/biofiber composites are suitable candidates as a potential replacement to the synthetic composites especially in various industries such as automotive, packaging, construction, and consumer products. It can also be used as an additive for thermoplastics. Additional investigations involve studying biological-inorganic interfaces to merge biological and inorganic materials while emphasizing on the design, production, and classification of novel amalgams [31]. Starch and cellulose are the most suitable renewable resources to create bioplastics. The cheapest source of biodegradable polymer in the marketplace today is starch and has applications in non-food industries as well. Cellulose plastics can be made by using cellulose from plant sources as an alternative to petroleum feed stocks [3, 7]. Vegetable oils have immense potential as a raw material to create biodegradable plastics, for example: plant oils and fats of sunflower, walnut, canola, sesame etc. Biocomposites created through biofibers and plant based bioplastics could be utilized in rigid packing, building, and transportation applications [3].

To manufacture products like decking, fencing, siding, window and door profiles etc., green composites are utilized. Some of the benefits obtained when biocomposites are utilized as construction materials are their low-cost, light in weight, eco-friendly, durability, and biorenewable [11].

### 4.2 Turning waste into bio composite

The bio composite was made using the waste materials. Billion-ton resource assessment conducted in 2011 has predicted sufficient supply of plant residues and

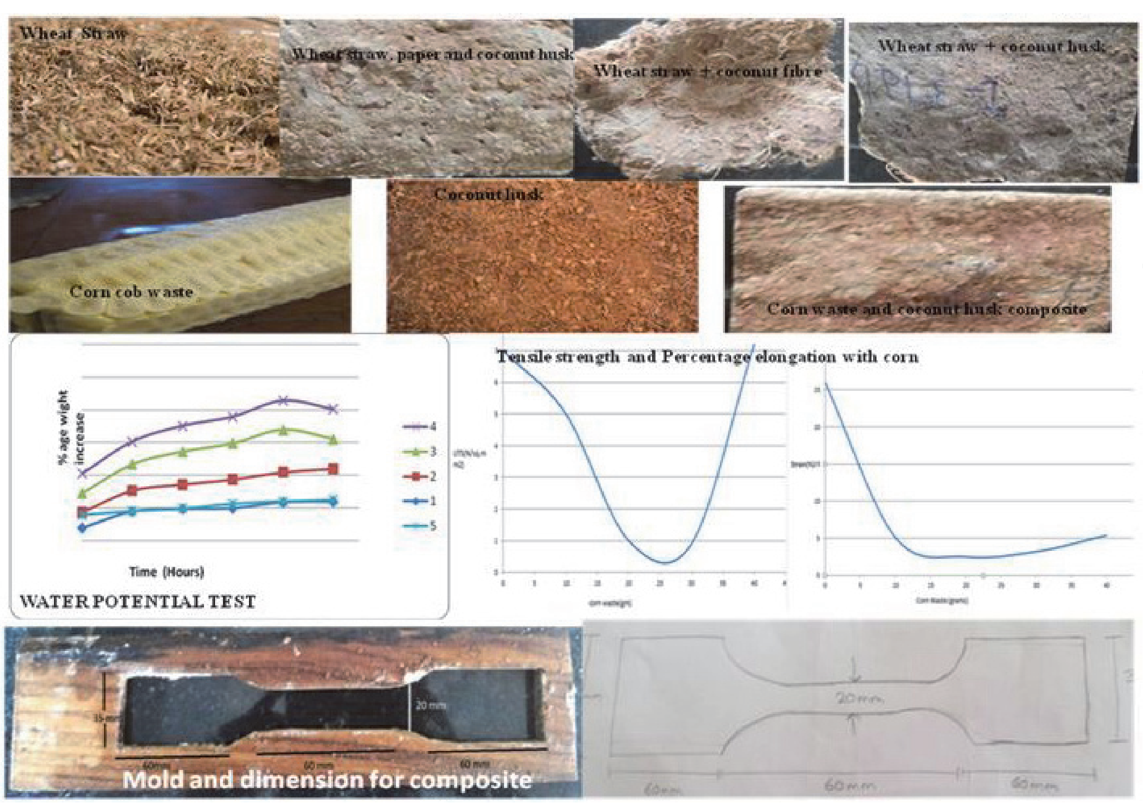



**Figure 5.**
*Synthesis of ecofriendly biocomposite using the organic waste and analysis of water potential, elongation and tensile strength of composite material.*

wastes within various price ranges. A supply of 180 million dry tons is expected at the end of 2030. When compared to primary plant residues, this supply seems low excluding animal manure. Corn stover, wheat straw accounts for at least three fourth of the residue resources whereas grains such as barley, sorghum, and wheat covers the rest. Availability of primary crop residues are enhanced by achieving continuous crop production and growth, large plots with less tillage, and no-till farming.

Green composites can be produced from different raw materials which are abundant in nature such as non-food crops and biorenewable sources. With recents trends in this particular field, biocomposite products could definitely find its place in the market across various applications. Different processing techniques and reinforcements of fibers/fillers allow the fiber at the correct price. Currently, there have been certain developments in the biopolymer industry.

In a study, the biocomposite ratio involving coconut blended with wheat husk was 15:85. Durability or toughness is affected by coconut husk due to it being fibrous in nature. Mixtures of wheat husk and water act as the matrix phase and binder. In terms of its mechanical properties, the product had displayed a strain of 26%, 7 $N/mm^2$ tensile strength along with a stair-step stress strain curve. The sample's performance might be because of various factors like how the axis is loaded, the relative motion among fibers through steady development across the loading axis. Crack proliferation due to interlinking of coconut husk has shown decent physical properties. A hybrid material is created by involving corn in the composite. Water absorption increases with increase in corn weight (**Figure 5**) [3].

## 5. Future prospects

Construction and automotive industry are the key markets for biocomposite materials. However, new prospects and applications will arise with certain future innovations and performance enhancement. Due to the accumulation of waste generated by this industry and their harmful effect on the environment which remains a growing concern, a lot of opportunities are going to emerge in this particular sector. Instances such as off-site construction method, for better quality and effortless installation and build, eco-friendly resources are required; although, these prospects could be affected by guidelines based on the present resources. A key target would be in replacing preservative-treated wood which provides a huge market growth. By placing strict limitations on utilization of preservatives such as arsenic containing products, provides immense opportunities for biocomposites to be used in applications especially when there is a threat of microbial attack.

Biocomposites can be incorporated into certain various complex technological applications by enhancing their mechanical functions such as producing new fiber types, processing methods, addition of additives etc. Solvent spinning process when applied to liquid crystalline cellulose creates high strength fibers which has been quite a hopeful research study. Resins can be formed by changing or enhancing the content of particular triglycerides and oils in produces by using biotechnology tools. The resins if altered appropriately would be cost effective and biodegradable compared to existing ones (**Figure 6**). Studies are being conducted to produce cheap biodegradable resins having decent mechanical characteristics by using novel methods. If successfully produced, the synthetic complexes can be replaced with these biodegradable alternatives.

Hybrid materials and products offer scope such as utilization of bio resins and bioplastics adhesives by replacing the existing fossil-based adhesives. Reclaimed fiber provides a decent opportunity to develop various eco-friendly, inexpensive

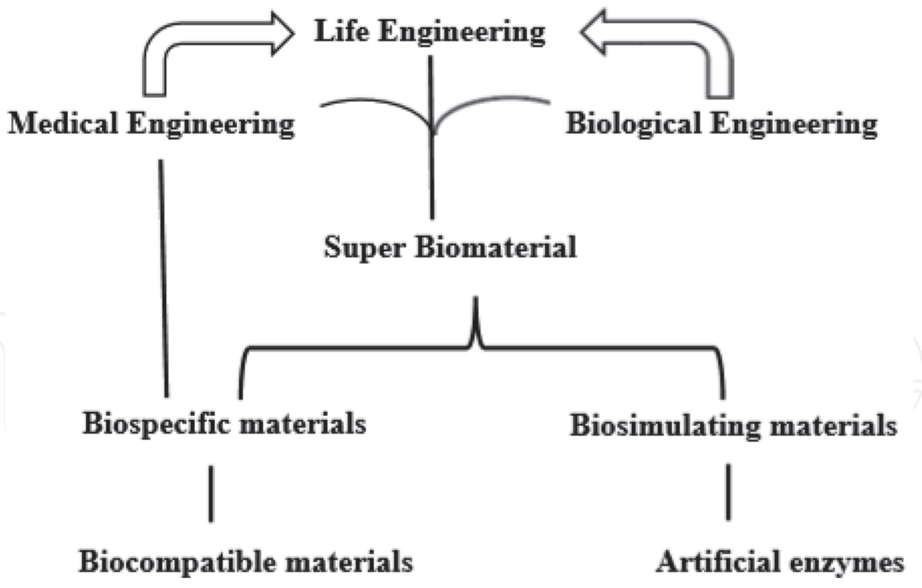



**Figure 6.**
*Scheme for hypothesizing for engineering and biocomposites.*

products by utilizing medium density fibreboards or the watercourses of the paper-making industry. Although sufficient prospects are there for these products to be in the market, cost effectiveness is a very important factor for its commercial production and hence the marketing strategy has to be made stronger accordingly. For successful commercialization, the biocomposites should be demonstrated through widespread training and education.

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