Chapter 22
Sisal Fiber Based Polymer Composites and Their Applications

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Abstract The natural resources of the World are depleting very fast due to the high rate of exploitation and low rate of restoration, leading to an increase in global warming and pollution hazards. In recent years, there has been increasing interest in the substitution of synthetic fibers in reinforced plastic composites by natural plant fibers such as jute, coir, flax, hemp, and sisal. Sisal is one of the natural fibers widely available in most parts of the world; it requires minimum financial input and maintenance for cultivation and is often grown in wastelands, which helps in soil conservation. Advantages of sisal fiber are: low density and high specific strength, biodegradable and renewable resource, and it provides thermal and acoustic insulation. Sisal fiber is better than other natural fibers such as jute in many ways, including its higher strength, bright shiny color, large staple length, poor crimp property, variation in properties and quality due to the growing conditions, limited maximum processing temperatures. In recent years, there has been an increasing interest in finding innovative applications for sisal fiber-reinforced composites other than their traditional use in making ropes, mats, carpets, handicrafts, and other fancy articles. Composites made of sisal fibers are green materials and do not consume much energy for their production.

The characteristics of composites depend on different parameters such as extraction of fiber, surface modification and the synthesis of composites. During synthesis, fiber length, orientation, concentration, dispersion, aspect ratios, selection of matrix, and chemistry of matrix have to be considered to achieve the required strength. Inorganic fibers have several disadvantages, including their nonbiodegradability, the abrasion in processing equipments, high cost and density, and the health problems caused to workers during processing and handling. Commonly used composites, these days are, glass, aramid, carbon, and asbestos fibers filled in thermoplastic, thermoset, or cement composites. Yet natural fiber composites with equivalent characteristics to synthetic fibre composites are not

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available. Most of the plant fibers are hydrophilic in nature and water absorption may be very high. This may be controlled by different methods of interfacial surface modification. Because of the low density and high specific strength and modulus. Sisal fiber is a potential resource material for various engineering applications in the electrical industry, automobiles, railways, building materials, geotextiles, defense and in the packaging industry. Present chapter discuss about the research work on sisal cultivation, fiber extraction, processing, sisal fiber characteristics, and the use of sisal fiber in thermoplastic and thermoset polymer composites for various engineering applications.

Keywords Characterization · Chemical treatment · Engineering applications · Fibre extraction · Sisal fibre · Surface modification · Thermoset and thermoplastic composites

Contents

Abbreviations

AMPRI	Advanced Materials and Processes Research Institute
Aq	Aqueous
BMC	Bulk Molding Compound
BPO	Benzoyl Peroxide
CBRI	Central Building Research Institute
CRIJAF	Central Research Institute for Jute and Allied Fibers
CSIR	Council of Scientific and Industrial Research
DSC	Differential Scanning Calorimetry
DTA	Differential Thermal Analyser
DCP	Dicumyl Peroxide
FSP	Fiber Saturation Point
GCL	Geosynthetic Clay Liners
HDPE	High Density Polyethylene
HC_5	Hostaprime
L	Longitudinal
LS	Longitudinal Section
LDPE	Low Density Polyethylene
IPIRTI	Indian Plywood Industries Research and Training Institute
MA-g-PP	Maleic Anhydride-Grafting Polypropylene
MAPP	Maleic Anhydride Polypropylene
MMA	Methylmethacrylate
NIRJAFT	National Institute of Research on Jute and Allied Fiber Technology
PE	Polyethylene
PEEK	Polyether Ether Ketone
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
R	Randomly
R&D	Research and Development
RTM	Resin Transfer Molding
SEM	Scanning Electron Microscope
TGA	Thermal Gravimetric Analysis
TIFAC	Technology Information, Forecasting and Assessment Council
TPA	Tons Per Annum
UFR	Urea–Formaldehyde Resin
UNIDO	United Nation Industrial Development Organization

22.1 Introduction

Natural fibers are classified based on their origins, whether they are plant, animal or mineral fibers. All plant fibers are composed of cellulose while animal fibers consist of proteins (hair, silk, and wool). Plant fibers include bast (or stem or soft sclerenchyma) fibers, leaf or hard fibers, seed, fruit, wood, cereal straw, and other grass fibers [1]. Over the last few years, a number of researchers have been involved in investigating the exploitation of natural fibers as load bearing constituents in composite materials. The use of such materials in composites has increased due to their relative cheapness, their ability to be recycled, and because they can compete well in terms of strength per weight of material [2]. Provided below is the classification of natural fibers based on origin:

- Vegetable (Cellulose) fiber: Fibers obtained from various parts of plants are known as vegetable fibers. These fibers are classified as (a) bast or stem fibers, (b) leaf fiber, and (c) fruit fiber
- Bast fibers: flax, hemp, jute, and ramie which are obtained from the bast tissue of bark
- Leaf fibers: sisal, pineapple, banana, and henequen obtained from the leaves
- Seed hair fibers: cotton, kapok, and coir which are obtained from seeds and the inner wall of fruits
- Animal (Protein) fiber: wool, silk
- Mineral (Asbestos) fiber

22.2 Sisal Fiber Plant

The sisal plant is shown in Fig. 22.1. Sisal fiber is a very strong and important leaf fiber [3]. It is extracted from the leaves of the sisal plant (*Agave sisalana*) and is very hard [5].

Fig. 22.1 Sisal plant

22.2.1 Variety, Availability, Volume and Yield

Variety

Sisal fibers are mainly obtained from *Agave sisalana,* which belongs to the genus Agave of the family of Agavaceae in which there are also other species such as *A. cantala, A. veracruz, A. americana, A. angustifolia, A. foucroydes.*

Availability

In India, sisal plant is not cultivated in an organized way; it is mostly grown on embankments, bunds, and roadsides, serving the purpose of soil conservation and for protection as hedge plantation. They are not optimally utilized and commercially exploited.

The sisal plant was introduced into East Africa (Tanganyika now Tanzania) in 1893 by Dr. Richard Hindorf. However, it originated in Central America, confined particularly to a zone between latitudes 10° and 25°N mainly in Mexico. Brazil is the largest world producer of sisal fiber. The Portuguese introduced sisal fiber in India around 1825. Sisal is the only crop that resists the semi arid climate and which is economically feasible in the unfertile and wasteland regions of the country.

Sisal is usually planted on the bunds or along the cattle proof trench-cum-mound structures for the basic purpose of either soil conservation or protection of the forested/cultivated lands against predatory animals or both. Sisal plants in India can be found mainly in the states of Orissa, Madhya Pradesh, Chhattisgarh, Andhra Pradesh, Bihar, Jharkhand, Maharashtra, Karnataka, and Tamilnadu [6]. In India, sisal is called *Ketki* and *RamBaan* in Hindi. A high yielding sisal hybrid *Bamrabum* was introduced in 1985 in all the sisal growing tracts of India by the Sisal Research Station of CRIJAF, Bamra (Near Sambalpur), Orissa.

Worldwide, there are more than 275 agaves present in different continents. Other agaves apart from Agave Sisalana prevalent in India include Agave vera-cruz (Elephant aloe, Gray aloe, and Railway aloe), Agave cantala (Maguey, Cantala/Cantula, Bombay aloe), Agave fourcryodes (Henequen, Mexican sisal), Agave augustifolia (Dwarf aoe), Agave americana (Century plant, American aloe), and Agave mexicana. Each of these species yields fiber of varying nature and properties.

Volume

Sisal is the sixth most commonly produced fiber globally and accounts for 2% of the world's plant fiber production [7]. According to the year 2007 data, the major sisal producers are [153]

Brazil – 130,000 tons
Mexico – 45,000 tons
China – 40,000 tons
Tanzania – 37,000 tons
Kenya – 27,000 tons
Madagascar – 15,000 tons

Other producers of sisal fiber include South Africa, Mozambique, Haiti, Venezuela, and Cuba.

Yield

Sisal plant produces 200–250 commercially usable leaves during its life cycle. The dried fiber represents only 4% of the total weight of the leaf. The dry fiber yield of the sisal plant varies between 2.5 and 4.0 ton/ha depending upon the plant population and management practices. Fibers (*Agave sisalana*) are extracted from the sisal plant leaves in the form of long fiber bundles called technical fibers [8]. The sisal leaf has a sandwich structure. Each leaf contains approximately 700–1,400 technical fibers with a length of 0.5–1 m. Every technical fiber contains numerous individual fibers about 3–8 mm in length and 10–30 mm in diameter [8, 9] and the total sisal leaf mass contains 2–4% technical fibers [150].

22.2.2 Cultivation and Harvesting

Sisal Propagation Mechanism

Sisal is a monocarpic perennial plant that produces a terminal tight rosette of narrow tapering spine after 6–9 years before it poles (flowers) and subsequently dies. Bulbils form on the elongated flowering inflorescence and when they become full-sized, they generally fall off. On average, a sisal plant generates 500–2,000 bulbils. These bulbils are collected and grown in nurseries. Sisal also produces suckers, which can be used for propagation. Suckers that begin to emerge from the second year of planting can be dug out and removed to be raised in a nursery [10, 11].

Sisal Nursery Raising

Sisal bulbils are raised in nursery beds with a spacing of about 25 × 25 cm^2. Bulbils may be preferred over suckers for planting. Bulbils or suckers can be collected about 6–8 months prior to the planting. The growth of bulbils is improved by mulching sisal nurseries with grass, paper or polythene. The sisal nursery needs irrigation throughout and weeding in nursery beds as necessary. The nursery incubation period is about 8 months depending upon the growth and vigor of the bulbils/suckers. The area of nursery to main plantation field may be approximately 1:10. Before plantation, the roots should be trimmed slightly and the withered leaves pulled off. Avoid plants with a damaged bole; it may pose the risk of rot.

The size of bulbils or suckers should be 40–50 cm in length and weigh about 600–1,000 g at the time of planting. Reliable quality sisal plantation materials (bulbils/suckers/plants) in India can be obtained on prior request from the Sisal Research Station of CRIJAF, Bamra (Near Sambalpur), Orissa, India [10, 11].

Sisal Growth and Climate Suitability

The sisal plant is drought resistant and tolerant of a variety of soils and climates, hence can flourish even in the arid and semiarid regions and subhumid tracts covering major parts of India. The sisal plant prefers well-drained and aerated soils because it is extremely sensitive to water logging and intolerant to marshy lands. Sisal can thrive in prolonged drought conditions and can survive at a low annual rainfall of 40–300 cm also. Sisal can withstand temperatures up to 40–50°C [12].

Land Preparation

Like any other plantation crop, proper land preparation is essential for commercial sisal plantations, where crops are planted in rows with a specified plant-to-plant distance. Land clearance, removal of boulders and rubble, ploughing of land, and digging out pits are the basic requirements of such plantations. Soil conservation contour bunds or field bunds can be utilized for sisal plantations with the excavated soil serving as support. Placing the excavated soil along cattle proof trenches can also serve as support to sisal plants. Arrangement of lines should be kept across the soil slopes and as parallel to contours as possible for effective soil and water conservation and better survival of sisal plants.

Sisal Spacing and Plantation

The right time for sisal planting is 20–30 days ahead of the rainy season. Sisal plantation can be done either in single rows or in double rows. A spacing of $2 \times 1\ \mathrm{m}^2$ corresponding to 5,000 plants/ha in a single row system is convenient and economical. The grown bulbils can be planted in the main field at the rate of 5,000 plants/ha with a double row system ($1 \times 2 \times 1\ \mathrm{m}^3$), where spacing of plant to plant is 1 m and row to row is 2 m. The most suitable spacing suggested is 2.5 m + ($1 \times 1\ \mathrm{m}^2$) and 3.0 m + ($1 \times 0.8\ \mathrm{m}^2$), which gives about 5,700 and 6,250 plants/ha respectively. The depth of plantation may be kept at 6–8 cm and enough care should be taken to ensure that the base of the spike is not buried in the soil; this will prevent rotting. Irrigation to the transplanted sisal saplings is essential if a severe and prolonged drought follows immediately after transplantation. About 2–3% of the total sisal planted should be available for gap filling in the event of initial mortality.

Intercropping

Intercropping can be done safely in the initial 2 years of the establishment of sisal plantations. Rainfed crops such as fodders, horse gram (kulthi, Macrotyloma *uniflorum*), castor (erandi, *Ricinus communis*), jowar (*Sorghum Bicolor*), bajra (*Pennisetum glaucum*) etc. can be raised as intercrops. Wherever irrigation water is unavailable, crop like beans (*Phaseolus coccineus L*), soybean (*Glycine max*), moong (*Vigna radiata*), urad (*Vigna mungo*), groundnut (*Arachis hypogaea*), etc. can be raised in the rabi season. The extent of intercropping in subsequent seasons depends on the growth of the sisal plants and their lateral spread. It is not advisable to raise water-intensive crops such as paddy, sugarcane, etc. that may cause drainage problems.

Fertilizers and Manuring

Under normal conditions, sisal does not require commercial fertilizers. But sisal responds very well to nitrogen, phosphorus, and potassium. In general, an application of 60–100 kg nitrogen, 30–35 kg phosphorus, and 60–100 kg potassium per ha per year is recommended.

Irrigation and Drainage

Sisal plantations require moderate irrigation in the first year immediately after plantation for proper establishment in case of severe drought or if the rains are interspersed with prolonged dry periods. Once established, sisal plantations do not require irrigation. However, irrigation in the winter and summer is beneficial for the growth of the plants and fetches healthy leaves of proportionately higher quantity.

Sisal plantations may not tolerate water logging and hence require proper drainage during continuous heavy rains and floods. Hence sisal plantations are established on the upper side of bunds and provision should be made for drainage of the entire field.

Weed Control

Removal of weeds and obnoxious plants, especially during the initial stage of plant growth, is advised as weeds compete for survival with sisal. Excessive weed competition leads to pale sisal due to nutrient deficiency. Hand weeding may be done depending upon the intensity of weed infestation and growth.

Harvesting of Sisal Leaves

The sisal plant normally yields up to 100 leaves and is ready for harvest after 2–3 years of planting. A sisal leaf is considered to be mature for harvest when it attains a length of about 1.0 m and forms an angle of about 60° with the main spike or when the color of the terminal spine changes to ash brown. A typical sisal plant yields 200–250 effective leaves in its lifetime in a period of about 10 years. Each sisal leaf contains 1,000–1,200 fibers. The plant matures fully after 3–4 years of growth.

A straight knife with a wooden handle is generally used to cut sisal leaves. It is better to nip the terminal spines before cutting the leaves. Harvesting should be initiated always from the lowermost whorls to the upper side; about 25 leaves are spared after the first cut and about 20 leaves at each subsequent cut. Where growth is unsatisfactory, more leaves are left after each cut. Each leaf is cut at a point about 3 cm from the bole through the upper part of its bulbous base, or just below the neck. Depending upon the growth, vigor, and maturity of the leaves, 2–3 cuttings per year may be undertaken. Care should be taken to avoid excessive cutting of the plants.

After cutting, the spike at the tip of the leaf is removed and leaves are bundled for transportation to the decortication site. This must be carried out as soon as possible since the cut leaves soon deteriorate if left exposed to the sun and decortication will become difficult. Sisal plantations in India yield about 2.5 ton dry fiber per hectare per year, with an annual net profit of Rs. 45,000 per ha. The fiber is usually obtained from sisal leaves by decortication in a machine called Raspador. The lustrous strands, usually creamy white, average from 80 to 120 cm in length and 0.2–0.5 mm in diameter.

Sisal-Production and Consumption Scenario

In 2007, sisal occupied sixth place among fibrous plants. The world's largest producer of sisal is Brazil (130,000 ton), followed by Mexico (45,000 ton) China (40,000 ton), Tanzania (37,000 ton), Kenya (27,000 ton), and Madagascar (15,000 ton). Smaller quantities of sisal fiber are also produced in South Africa, Mozambique, Haiti, Angola, Uganda, Malawi, Venezuela, Jamaica, Puerto Rico, France, Indonesia, Cuba, and India. Experts opine that the current worldwide demand for sisal fiber is about one million tons. Currently, high prices are being offered for the crop in the global market, in which the sisal fiber now fetches between 650 and 900 US$/ton up from 150 US$/ton in the 1990s.

India needs about 25,000 ton of sisal fiber of annually for internal consumption, whereas production is less (5,000 ton). The fiber was priced at Rs. 9,000–10,000 per ton in 1988–1989, which rose to Rs. 27,000 per ton in 1996–1997, showing a phenomenal rise in its price. The current price is about Rs. 35,000 per ton, indicating the decadal growth in price.

22.2.3 Fiber Extractions and Processing

Sisal fiber can be extracted from its leaves by the following methods [13].

Retting

Water retting is a traditional biodegradation process involving microbial decomposition (breaking of the chemical bonds) of sisal leaves, which separates the fiber from the pith. The fibers are washed and processed further. This process takes 15–21 days for a single cycle of extraction and degrades the quality of fiber. Retting is a very slow, water intensive process, unhygienic, and not eco-friendly. Fiber extracted by this method is poor in quality [14, 15].

Boiling

In this method leaves of sisal plant are boiled, subsequently beating is done then after washing and sun drying we may get the usable clean fiber. This method is not suitable for large-scale extraction [15].

Mechanical Method

Mechanical extraction involves inserting leaves into the Raspador machine and pulling the raw material out. The mechanical extraction method is safe, this process does not deteriorate the fiber quality and is suitable for small-scale operations. The Raspador, run by an electric motor, is efficient, versatile, safe for labor, and cost-effective; it takes minimum time and is an eco-friendly process. In addition, residues are available after extraction of fiber of which about 96% is useful for other applications, such as biogas generation, composting, and isolation of a steroid hecogenin. The residue is also used for making paper, paperboard, and biodegradable polymer, wax, etc. [8, 16–19]. The extraction of sisal fiber using Raspador machine is shown in Fig. 22.2.

Fig. 22.2 Extraction of fiber from sisal leave

Fibre extraction using Raspador machine

Harvested sisal leaves

Sisal fibre

22.3 Sisal Fiber Composition, Structure and Properties

22.3.1 Composition

A sisal plant can produce about 200–250 leaves. Each leaf composed of 3–4% fiber, 0.75% cuticle, 8% dry matter and 87.25% water [20]. Normally, the weight of a leaf is about 600 g and it will yield about 3% by weight of fiber. Each leaf contains about 1,000 fibers [21], and each fiber has a longitudinal approximately cylindrical shape. Physically, each fiber cell has four main parts: the primary wall, the thick secondary wall, the tertiary wall, and the lumen [3]. Its microstructure consists of parallel cells and a cuticle interface in the form of a continuous network around each cell. It is tough and strong because of its flexible interface and solid cells [22].

Sisal varies in quality. The large variations in its chemical compositions are because of its different sources, age, extraction methods, etc. [23]. For example, Wilson [13] indicated that sisal fiber contains 78% cellulose, 8% lignin, 10% hemicelluloses, 2% waxes, and about 1% ash by weight, whereas Rowell et al. [24] found that sisal contains 43–56% cellulose, 7–9% lignin, 21–24% pentosan, and 0.6–1.1% ash. The work carried out by Chand and Hashmi [25] showed that the cellulose and lignin contents of sisal vary from 49.62 to 60.95% and 3.75 to 4.40%, respectively, depending on the age of the plant.

According to Mohanty et al. [26] sisal fiber contain around 66–78% cellulose, 10–14% hemicellulose, 10–11% lignin, 10% pectin, 10–22% moisture content, and 2% waxes.

22.3.2 Structure

All natural fibers are cellulosic in nature. The major constituents of natural fibers are cellulose and lignin. During the biological synthesis of plant cell walls, polysaccharides such as cellulose and hemicellulose are produced simultaneously. Lignin fills the space between the polysaccharide fibers, cementing them together. This lignification process causes a stiffening of cell walls and the carbohydrate is protected from chemical and physical damage.

Cellulose forms slender rod-like crystalline microfibrils. The crystal structure of naturally occurring cellulose is known as cellulose I. Lignin is a high molecular weight phenolic compound but the exact chemical nature of lignin still remains obscure. Its associated hydroxyl and methoxy groups characterize lignin. It is believed that the structural units of the lignin molecule are derivatives of 4-hydroxy-3-methoxyphenylpropane, and the composition of the external surface of the cell wall is a layer of ligninaceous material and waxy substances that bond the cell to its adjacent neighbors. Hence, this surface does not form strong bonds with a polymer matrix [26].

22.3.3 Properties

Cellulose is a hydrophilic glucon polymer consisting of a linear chain of 1,4-β anhydroglucose units, which contain alcoholic hydroxyl groups. These hydroxyl groups form intermolecular and intramolecular hydrogen bonds with the macromolecule itself and also with other cellulose macromolecules or polar molecules. Therefore, all natural fibers are hydrophilic in nature. Although the chemical structure of cellulose from different plants fiber is the same, the degree of polymerization varies. The mechanical properties of a fiber are significantly dependent on the degree of polymerization.

Lignin is a biochemical polymer that functions as a structural support material in plants. Lignin is a high molecular weight phenolic compound, generally resistant to microbial degradation. Lignin is believed to be linked with the carbohydrate moiety through two types of linkages, one alkali sensitive and other alkali resistant. The alkali sensitive linkage forms an ester type combination between lignin hydroxyls and carboxyls of hemi-cellulose uronic acid. The ether type linkage occurs through the lignin hydroxyl combining with the hydroxyl of cellulose [26]. The plant fibers absorb moisture as the cell wall polymers contain hydroxyl and other oxygenated groups that attract moisture through hydrogen bonding. The hemicelluloses are mainly responsible for moisture absorption in the plant fiber, but the other noncrystalline cellulose, lignin, also plays a major role in this. In general, plant fibers absorb moisture up to a certain level – the Fiber Saturation Point (FSP). Absorption above or below the FSP causes swelling and shrinking of the fiber respectively, and this leads to dimensional instability in the final composite product made of the natural fiber as a reinforcing element. When plant fibers are exposed to the outdoors, they undergo photochemical degradation caused by ultraviolet radiation. The degradation takes place primarily in the lignin component, which is responsible for the characteristic color changes. As the lignin degrades, the surface becomes richer with cellulose content – this results in the rough surface of the composite and also accounts for a significant loss in surface fibers [27].

22.4 Fiber Surface Modification Methods

Research and engineering interests have been shifting from monolithic materials to fiber-reinforced polymeric materials because the latter offer many advantages: they are lightweight, have low abrasiveness, are combustible, do not cause much wearing of the machine or health hazards during processing and application, and are eco friendly, making disposal easy. However, the most important problem with these plants fiber composites is the poor fiber–matrix adhesion; insufficient adhesion between hydrophobic polymers and hydrophilic fibers results in poor mechanical properties of the natural fiber-reinforced polymer composites. However, surface modification of the fiber by various physical and chemical treatments improves these properties [21, 28].

22.4.1 Physical Methods of Modification

A physical treatment changes the structural and surface properties of the fiber and thereby treated fibre influences the mechanical properties of composites. Physical methods involve heat treatment, cold plasma treatment, surface fibrillation, electric discharge, and gamma radiation treatment.

Low Temperature Plasma Treatment

Plasma treatment of the surface of plant fiber can be done without changing its bulk properties. The plasma discharge can be generated by cold plasma treatment. In plasma treatment, ionized gases with an equivalent number of positive and negatively charged molecules are used and these charged molecules react with the surface of the present material. The distinguishing feature between the two categories of plasmas is the frequency of the electric discharge. High-frequency cold plasma can be produced by microwave energy, whereas a lower frequency alternating current discharge at atmospheric pressure produces corona plasma [29].

Low temperature plasma treatment mainly causes chemical implantation, etching, polymerization, free radical formation, and crystallization; whereas sputter etching brings physical changes such as surface roughness which in turn leads to increased adhesion [30]. Low temperature plasma is a useful technique to improve surface characteristics of the fiber and polymeric materials by utilizing ingredients such as electrons, ions, radicals, and excited molecules produced by electric discharge. Low temperature plasma can be generated under atmospheric pressure in the presence of helium. The action of these plasma involves the removal of protons and creation of unstable radicals that convert functional groups such as alcohols, aldehyde, ketone, and carboxylic acids [30]. Corona treatment changes the surface energy of the cellulosic fibers, which in turn affects the melt viscosity of the composites. Corona treatment modifies surface composition resulting in an improvement in the surface properties of the composite [149].

Electric Discharge

Electric discharge methods are used for cellulose fiber modification to increase the melt viscosity of the fiber and to improve its mechanical properties [31].

Gamma Treatment

Fibers were treated with NaOH or just washed with water. They were then dried for 48 h at 75°C. The sample was irradiated by integral doses up to 10, 25, 50, 60, and 70 kGy with a dose rate of 4.8 kGy/h in an oxygenated atmosphere and at room temperature [32]. Albano et al. [32] reported the mechanical, thermal, and morphological behavior of blends of polypropylene filled with wood flour and sisal fiber composite with different doses of gamma irradiation (10, 25, 30, 50, 60 and 70 kGy) at room temperature and in the presence of oxygen. It was found that low irradiation doses improved the mechanical behavior of the compound or composites and the thermal study was acceptable [148]. Gamma irradiation is therefore a promising technology to modify composites [32, 148].

Chemical Methods of Modification

To modify the fiber surface and its internal structure various treatments have been carried out, including alkalization, acetylation, acrylation, permanganate, cyanoethylation, and the use of silane coupling agents. In general, fiber treatments can increase interphase adhesion and also lead to penetration of the matrix resin into the fibers and influence the mechanical properties of fiber reinforced composites [33].

Alkali Treatment

Alkali treatment improves the surface structure of sisal fiber and decreases its diameter. Due to the removal of cementing substances from the inner surface of lumen, polymer can easily penetrate into the cavities of sisal fiber. Moreover, alkali treatment improves the fiber wetting. Extensive work has been done by several researchers who reported that sisal fiber was treated with different concentrations of NaOH (% w/w 0.25, 0.5, 1.0, 2.0, 5.0, 10) solution for a fixed time period, washed with water, and dried in an air oven or vacuum dried [34–40]. This process is known as alkalization or mercerization.

Surface modification processes usually affect the morphology, mechanical properties, and thermal degradation of natural fiber or plant fiber. The surface of the sisal fiber was wrapped with some cementing substances before alkali treatment, a the epidermal cells of sisal fiber combined closely with the neighboring cells. Due to mercerization, fibrillation occurs in which the fiber bundle splits into separate fibrils. The reduced diameter of the fiber increases the aspect ratio which leads to the development of a rough topography which further results in better fiber–matrix interface adhesion and an increase in mechanical properties [41]. Alkali reagents affect the chemical composition of the fiber, the degree of polymerization, and the molecular orientation of the cellulose crystallite because the cementing substances such as lignin and hemicelluloses are removed during the treatment process [42]. Sydenstricker et al. [35], found that the tensile strength of sisal fiber increases after 0.25–2% alkali treatment for the duration of 60 min but on further increasing the concentration, these properties show a decrease as reported in the Table 22.1. Garcia et al. also reported that 2% alkali treatment for 90 s at 1.5 MPa pressure was suitable for degumming and defibrillation of individual fibers [43]. Many researchers have reported that alkali treatment can increase amorphous cellulose and decrease crystalline cellulose and network hydrogen bonding [41, 44–47].

Acetylation

Acetylation is mainly applied to stabilize the cell wall against moisture absorption for improving its stability and environmental degradability [48–52]. In acetylation, acetic anhydride substitutes the hydroxyl group of the cellulose with acetyl groups that modify the properties of fibers so that they become hydrophobic [50]. Moisture absorption of fiber reduces after acetylation, which is beneficial for composites application. It was reported that after acetylation reduction in moisture uptake was found to be around 50–65% [53].

It is reported that in acetylation treatment, sisal fiber was soaked in glacial acetic acid at room temperature, decanted, and then soaked in acetic anhydride containing a few drops of concentrated sulfuric acid [34]. In another method, sisal fiber was treated with NaOH for 5 min, washed with distilled water and treated with glacial acetic acid containing a few drops of sulfuric acid as neutralizing agent, then dried and soaked in acetic acid solution, and then washed and air dried. Fiber treated in this manner showed an enhancement in tensile strength (423 MPa) [38]. Mishra et al. have done the acetylation of dewaxed–mercerized sisal fiber. They soaked alkaline treated fiber in glacial acetic acid for 1 h at 300°C and after 1 h it was decanted and soaked for 5 min in acetic anhydride containing one drop of concentrated sulfuric acid [54].

Permanganate Treatment

In permanganate treatment, mercerized fiber was treated with acetone solution of $KMnO_4$ for 1–5 min and air-dried after separation from solution [3, 4, 44, 55–59]. Kalaprasad and Thomas [34] studied the uses of permanganate-treated sisal fiber for making composites with a polyethylene matrix. In a polyethylene matrix, MnO_4^- ion is responsible for initiating permanganate-induced grafting of polyethylene into sisal fiber [34]. Joseph et al. studied permanganate treatment and found that the tensile strength of permanganate-treated sisal was around 38.80 MPa which was found to be higher than that of the untreated sisal fiber composites [3]. Paul et al. soaked alkaline-treated sisal fibers in different solutions of acetone containing 3.3 g, 6.25 g, and 12.5 g $KMnO_4$ in 100 ml acetone. It resulted in reduction of

Table 22.1 Effect of different chemical treatments on sisal tensile strength

S. No.	Treatments	Concentration (%)	Density (g/cm^3)	Tensile strength (MPa)	References
1.	Alkali (60 min)	0.25	–	350	Sydenstricker et al. [35]
		0.5	–	372	
		1	–	366.2	
		2	0.19	375.4	
		5	–	328.0	
		10	1.16	296.9	
	Alkali (4 h) (60°C)	2	1.27	391	Rong et al. [38]
2.	Acrylation – *N*-isopropyl acryl amide (60 min)	1	1.18	331.2	Sydenstricker et al. [35]
		2	1.18	347.8	
		3	1.18	256.4	
3.	Acetylated (5 min)	50% aq acetic acid solution	1.32	423 ± 27.3	Rong et al. [38]
4.	Cyanoehtylation (30 min)	4% NaOH saturated solution with sodium-thiocyanate	–	375.8 ± 31.4	Rong et al. [38]
5.	Silane treated (5 min)	2	–	387.5 ± 34.5	Rong et al. [38]
6.	Heating of sisal fiber (4 h) (150°C)	–	1.31	535 ± 42.3	Rong et al. [38]
7.	Acrylonitrile grafting (10 min) (50–70°C)	5	–	612.75	Rong et al. [38]
		10	–	602.61	Rong et al. [38]
		25	–	589.15	Rong et al. [38]
8.	NaOH + ethyl Alcohol	(10/5)	–	522.5 ± 155.9	
9.	Hot water treatment (100°C)	–	–	764.9 ± 162.2	Present study by authors
10.	NaOH (10 min)	5	–	859.2 ± 121.7	Present study by authors
11.	NaOH + lactic acid (5 days)	(10/5)	–	549.4 ± 139.9	Present study by authors
12.	Polyethylene glycol	10	–	809.1 ± 122.5	Present study by authors
13.	Ethyl acetate + acetic acid + water	(5/1/4)	–	512.1 ± 150.8	Present study by authors

hydrophilicity of the fiber –the water absorption of fiber-reinforced composite is reduced. The hydrophilic tendency of sisal fiber decreases with increasing $KMnO_4$ concentration. But at a higher concentration of permanganate, degradation is observed which results in the formation of polar groups between fiber and matrix [56, 57].

Stearic Acid Treatment

It is reported that a solution of stearic acid in ethyl alcohol (4% by weight of fiber) was used to treat sisal fiber and the results showed that stearic acid-treated sisal showed better compatibility between sisal fiber and matrix [34].

Silane Treatment

Coupling agents can enhance the degree of cross-linking at the interface and improve bonding. Silane was found to be the most effective among many coupling agents to modify the natural fiber–matrix interface. The efficiency of silane treatment was high for the alkaline-treated fiber than for untreated fiber because more reactive sites can be generated for silane reaction [33].

After silane treatment, the number of cellulose hydroxyl groups in the fiber–matrix interface may reduce. In the presence of moisture, alkoxy groups convert into silanols, and after that the silanol reacts with the hydroxyl group of the fiber, forming stable covalent bonds to the cell wall on the fiber surface [62]. After silanation, swelling of fiber decreases because a cross-linked network of covalent bonding between the matrix and the fiber is created [33]. Silanes were effective in enhancing the interface properties [63–66]. Alkoxy silanes can easily form bonds with hydroxyl groups. After hydrolysis, silanes can form a polysiloxane structure by reaction with hydroxyl groups of fiber [44]. After silane application, hydrocarbon chains allow the fibers to absorb more water, which means that its chemical affinity to the polymer matrix is improved [33].

Earlier too, several researchers studied silane treatment. One reported that sisal fiber was mixed with a mixture of silane, CCl_4 and dicumyl peroxide and heated and dried in an oven [34]. In other experiment, sisal fiber was soaked in a solution of amino silane and alcohol at pH range up 4.5 to 5.5, and the fiber was oven dried after separation [34, 39, 67]. Some researchers treated the surface of the fiber with 1% silane and 0.5% dicumyl peroxide, in a mix of methanol/water (90/10 w) at pH 3.5 with acetic acid, under agitation [39]. Another study showed that silane treatments were done using silane [Fluoro silane (F8261)], amino propyl tri-ethoxy silane, and vinyl triethoxy silane mixed with an ethanol/water mix (of ratio 6:4) for 1 h at pH 4 in acetic acid [25]. The general formula for silane coupling agent is $YR_1Si\ (OR_2)_3$, where Y is the polymerizable vinyl group of silane and OR_2 is a hydrolyzable group. During silane treatment, the OR_2 group of the silane may hydrolyze to some extent to form silanols. The resulting –OH groups of silanol or $–OR_2$ groups of unhydrolyzed silane interact with cellulose through their –OH groups by the formation of hydrogen bonds. Results showed that 2% silane treated sisal shows tensile strength 387.5 MPa [34, 114].

Peroxide Treatment

Many researchers treat cellulose fiber with peroxide because the process is simple and the mechanical properties of the fiber improve. In peroxide treatment, organic peroxide easily decomposes into peroxide free radicals, which can easily react with the hydrogen group of the matrix and cellulose fiber.

In one experiment, fibers were treated with a solution of benzoyl peroxide and dicumyl peroxide in acetone for about half hour after alkali treatment [44, 55–57]. High temperature favors decomposition of peroxides [74]. Studies on sisal fiber treatment were performed and composites were developed using benzoyl peroxide and dicumyl peroxide and toluene solvent with polyethylene at the time of mixing with fiber. The peroxide-treated matrix showed higher viscosity than untreated composites because of the grafting of polyethylene onto sisal fiber in the presence of peroxide [34]. Benzoyl peroxide-treated sisal fiber showed a tensile strength of 40.90 MPa [60, 61].

Acrylation

Acrylation of fiber is initiated by free radicals of the cellulose molecule [44, 68, 69]. The surface energy of fibers was increased after chemical treatment, providing better wettability and high interfacial adhesion [33].

Sisal fiber was treated at different percentage (1, 2, 3% w/w) of *N*-iso propyl acryl amide aqueous solution at room temperature [35]. It was observed that the treatment with *N*-iso propyl acryl amide 1, 2, and 3% gradually affected the fiber, exposing its inner layers. However, the 3% treatment significantly altered its surface. Pull-out tests in polyester resin were performed and found effective in improving interfacial adhesion [35]. Sreekala et al. used acrylic acid for acrylation [44]. The 2% acryl amide treatments showed optimum strength (347.8 MPa) because it showed higher tensile strength in 1% and 3% [44].

Dewaxing

It is very important to dewax the sisal fiber to improve its properties. One of the researchers studied the dewaxing of sisal fiber with a 1:2 mix of ethanol and benzene at 72 h at 50°C. The fiber was then washed in distilled water and air dried [36, 37].

Bleaching

In bleaching fiber is usually treated with sodium chlorite and links are developed between lignin and carbohydrates. Removal of noncellulosic compounds by chemical treatments resulted in improvement of mechanical and physical characteristics as well as of fiber strength [33].

The bleaching of sisal fiber was done with sodium chlorite solution with a liquor ratio 25:1 at 75°C for 2 h. Further, the fiber was washed with distilled water, then treated with a 2% solution of sodium sulfite, and then vacuum dried. Zahran et al. developed a bleaching process in which activation of sodium chlorite was done by hexamethylene tetramine in the presence of a nonionic wetting agent [70]. The results revealed that bleached sisal fiber showed less tensile strength due to the loss of the cementing material. But the composite with bleached sisal shows enhanced flexural strength because of less stiffness and more flexible character of fiber after delignification. Moreover, high impact strength was achieved which may be due to the better bonding between the bleached fiber and the matrix [36, 37].

Cyanoethylation

Efforts were made to improve the strength of the sisal fiber for its value addition in engineering applications. The earlier work showed that the defatted fiber were refluxed with acrylonitrile, where pyridine was used as catalyst at a temperature range of 50°C–70°C for 2 h. The washed fiber using acetic acid and acetone followed by washing was vacuum dried to get cyanoethylated fibers at three different temperatures [36, 37]. Cyanoethylated sisal fiber showed a tensile strength of about 375.8 MPa [36, 37].

Isocyanate Treatment of Sisal Fiber

Isocyanate is very susceptible to reaction with the hydroxyl group of cellulose and lignin in the fibers and forms strong covalent bonds, hence increases fiber–matrix interface adhesion. In isocyanate treatment, the isocyanate group acts as a coupling agent [71, 72], and fiber is treated with the polymethylene–polyphenyl–isocyanate ($C_{15}H_{10}N_2O_2$) solution at 50°C for 30 min duration [72].

Benzoylation of Sisal Fiber

In benzoylation, benzoyl chloride is used for fiber treatment. The benzoyl group interacts with the hydroxyl group of fibers and decreases the hydrophilic nature of the fiber.

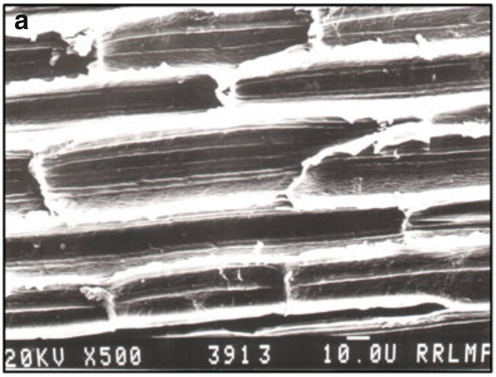
Joseph et al. [41] have done benzoylation of fiber, in which fiber was soaked in 18% NaOH solution followed by filtration, washing, and drying. Treated fiber was agitated in a solution of 10% NaOH and 50 ml benzoyl chloride. The reaction between hydroxyl of cellulose and benzoyl groups takes place, resulting in decreased hydrophilicity [41, 73]. In one experiment, alkali treatment of fiber was done before benzoylation for the activation of fiber. After benzoylation extra benzoyl chloride can be removed by the treatment of fiber with ethanol for 1 h and finally washed with water and dried in oven at 80°c for 24 h [74].

Polymeric Coating on Sisal Fiber

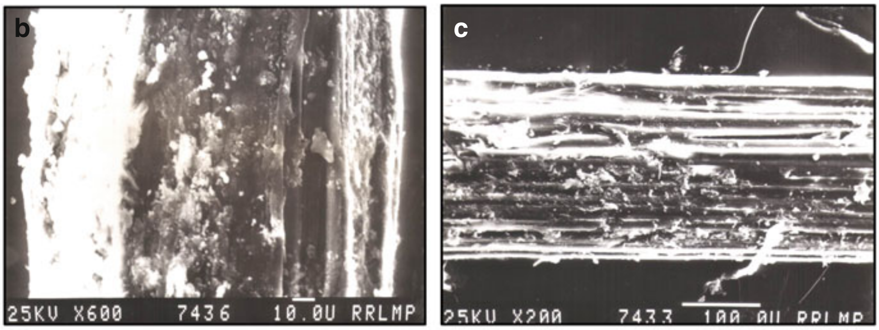
The strength of composites mainly depends on the interfacial bonding of fiber with the matrix and tensile modulus of fiber. Research work has been carried out to improve interfacial bonding of pretreated fiber with different polymer coatings (acrylic and polystyrene). Improvement in interfacial bonding between the fiber and matrix is clearly visible in SEM micrographs Fig. 22.3. To impart hydrophobicity and improve the interfacial bonding, sisal fibers were coated with acrylic resin and polystyrene resin. NaOH treated fibers were dipped in 3%, 5%, and 7% acrylic resin and polystyrene resin followed by air drying. The polymeric coatings on sisal fiber were done to overcome the hydrophillic nature of sisal fiber and improving the mechanical properties and interfacial bonding.

Tensile test machine is shown in Fig. 22.4 (Make AMETEK LLYOD/LRX, UK). The tensile strength of sisal fiber treated with 3%, 5%, and 7% acrylic coated NaOH-treated sisal fiber is shown in Fig. 22.5. Results revealed that the tensile strength of treated fiber was found to be increased maximum in NaOH-treated fiber with 5% acrylic coating (Fig. 22.5) [75].

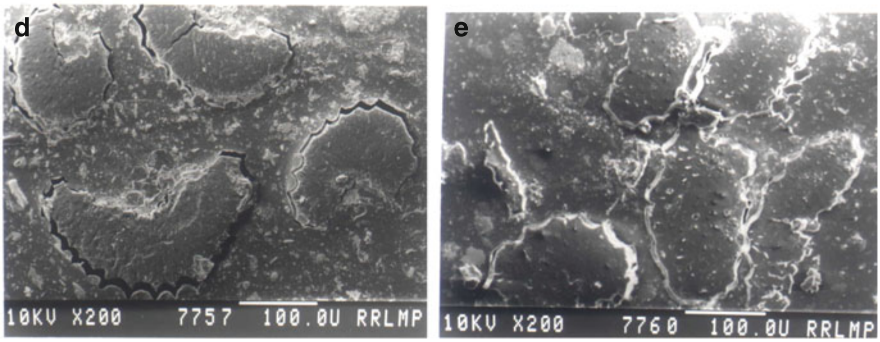
The effect of different chemical treatments on the tensile properties of sisal fiber is shown in Table 22.1. However, there is a wide variation in the tensile strength of the treated fiber And the prime factors responsible for such variations are the age of the fiber; climatic condition under which it is grown; the technique of extracting fiber from the sisal leaf; precision and treatment handling techniques; and finally the untreated fibers being not of the same properties to compare with the treated fiber, especially where the work was conducted in different parts of the world. Nevertheless, the tensile strength of untreated sisal fiber, cultivated at AMPRI Bhopal, Central India, over a period of 5 years, and after harvest extracted using the Raspador machine was 501.3 ± 119.5 MPa (Table 22.2).



Uncoated Sisal fibre (LS)



5% Acrylic Coated Sisal fibre (LS) 5% Polystyrene Coated Sisal fibre (LS)



Cross Section of Uncoated Sisal fibre Cross Section of Polymer Coated Sisal fibre

Fig. 22.3 SEM microstructure of sisal fiber

It is apparent from the work done by the various researchers that the tensile strength of the sisal fiber after different chemical treatment varies from 256 to 612 MPa [35, 38]. In fact, under NaOH treatment, the tensile strength of sisal fiber was as high as 859.2 ± 121.7 MPa.

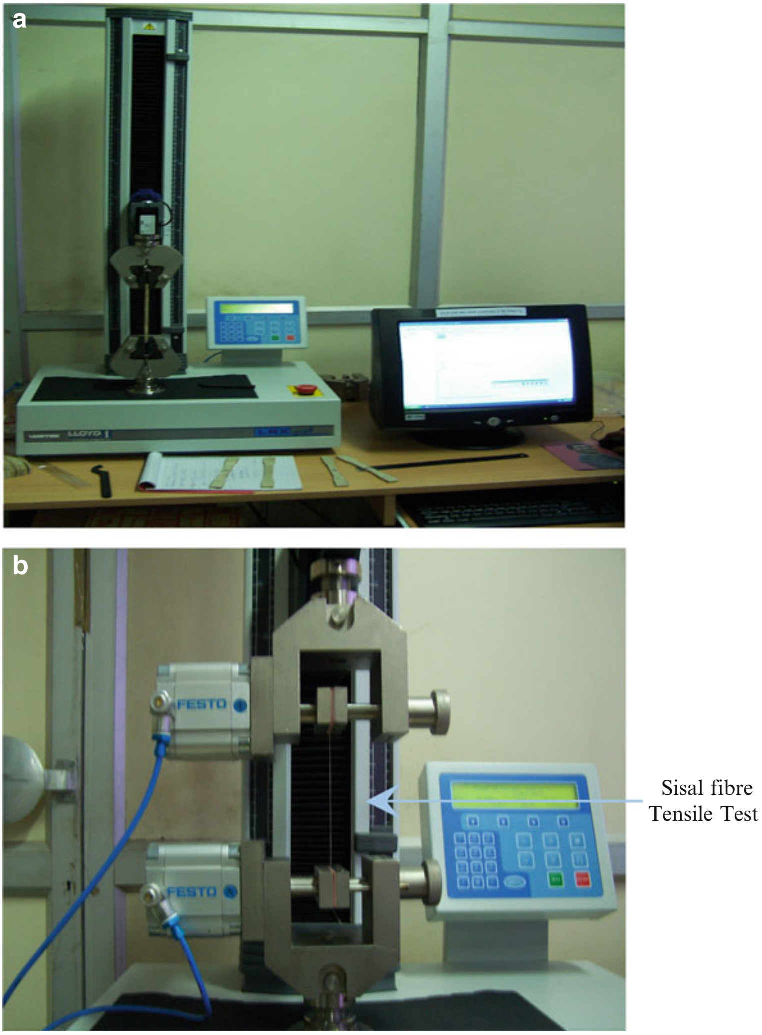


Fig. 22.4 Fiber testing machine

22.4.2 Physico-Chemical and Mechanical Properties of Sisal Fiber and Its Comparison with Other Natural Fiber

The chemical composition and cell structure of plant fiber is very interesting as each fiber is a composite in which rigid cellulose micro fibrils are reinforced with soft lignin and hemicellulose matrix. Also, the micro fibrils are helically wound along the fiber axis. Sisal fiber is equipped with high content of cellulose (60–80%), hemicellulose (10–25%), and lignin (7–14%) with high tensile strength and modulus in comparison with other natural fibers. This has led to a great interest among the

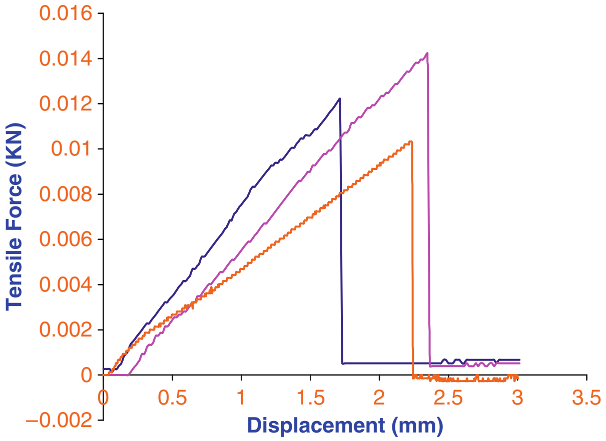


Fig. 22.5 Tensile strength of 3%, 5% and 7% acrylic coated NaOH treated sisal fiber

researchers as its properties make sisal suitable for reinforcement in composites for various applications [38]. The chemical composition of sisal fibers is reported in Table 22.3.

Properties of Sisal Fibers

Sisal is a strong fiber traditionally used for making rope, cordage, and twine. It is also used to manufacture coarse fabric, rugs, carpets, handicrafts, mats, fishing nets, etc. The sisal pulp left after fiber extraction is used for making paper/paperboards [17], hecogenin (a cortioco steroid) [17], wax [17], biodegradable polymer [81], biogas [82], and vermicompost [83].

The mechanical, thermal, and dielectric properties of sisal fiber have been studied in detail. X-ray diffraction, Infrared Spectroscopy, Thermal Gravimetric Analysis, Scanning Electron Microscopy, Differential Scanning Calorimetry, Dynamic Mechanical Analysis etc., have been used to determine the characteristics of sisal fiber and provide theoretical support for processing and application of the fiber.

The mechanical properties of sisal fiber tested by several researchers have been compiled and shown in Table 22.2. The results show that the tensile strength of sisal fiber varies from 100 to 700MPa, tensile modulus is in the range of 9–40 GPa, and elongation at break in the range of 2–14%. It may be noted that the tensile properties of sisal fiber may not be uniform along its length. The fibers extracted from the lower part of the leaf may exhibit a lower tensile strength and modulus but a higher fracture strain. The fiber becomes stronger and stiffer at midspan and the fibers extracted from the tip have moderate properties. It is reported that the tensile strength, modulus, and toughness of sisal fibers decrease with increasing temperature [26].

Silva et al. [84] studied the monotonic tensile behavior of a high performance sisal fiber. Tensile tests were performed on a micro force testing system using four

Table 22.2 Mechanical properties of Sisal fiber

S. No.	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	References
1.	550 ± 100	24 ± 0.4	2.4 ± 0.4	Oksman et al. [9]
2.	400–700	7–20	2–14	Oksman et al. [9]
3.	400–700	9.0–38.0	2.0–14	Li et al. [76]
4.	400–700	9.0–20	5–14	Joseph et al. [77]
5.	530–630	17–22	3–7	Jacob et al. [40]
6.	400–700	9–20	5–14	Paul et al. [56, 57]
7.	434	17.5	–	Ganan et al. [78]
8.	580	–	4.3	Joseph et al. [3, 4]
9.	100–700	25–50	3–6	Li et al. [76]
10.	511–635	9.4–22.0	2.0–2.5	Shibata et al. [95]
11.	500 ± 70	13.2 ± 3.1	4.8 ± 1.1	Gonzalez et al. [150]
12.	450–700	7–13	4–9	Nair et al. [79]
13.	511–700	3.0–98	2.0–2.5	Bogoeva et al. [94]
14.	340 ± 7	12.8	6–7	Idicula and Boudenne [80]
15	501.3 ± 119.5	50.57 ± 3.27	0.78 ± 0.41	Present study by authors

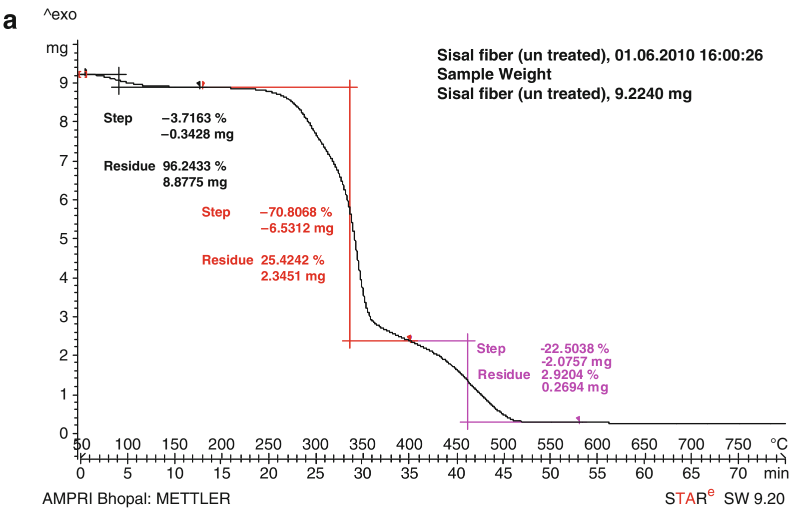
Table 22.3 Chemical composition of sisal fibers

S. No.	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	References
1.	47–78	10–24	7–11	0.6–1	Li et al. [76]
2.	85–88	4	4–5	1	Joseph et al. [77]
3.	78	10	8	–	Jacob et al. [40]
4.	66–72	12	14–10	–	Paul et al. [56, 57]
5.	70	12	–	–	Joseph et al. [58, 59]
6.	60	28	8	0.5	Gonzalez et al. [150]
7.	73	10.1	7.6	3.1	Sydenstricker et al. [35]
8.	65	12	9.9	–	Idicula and Boudenne [80]

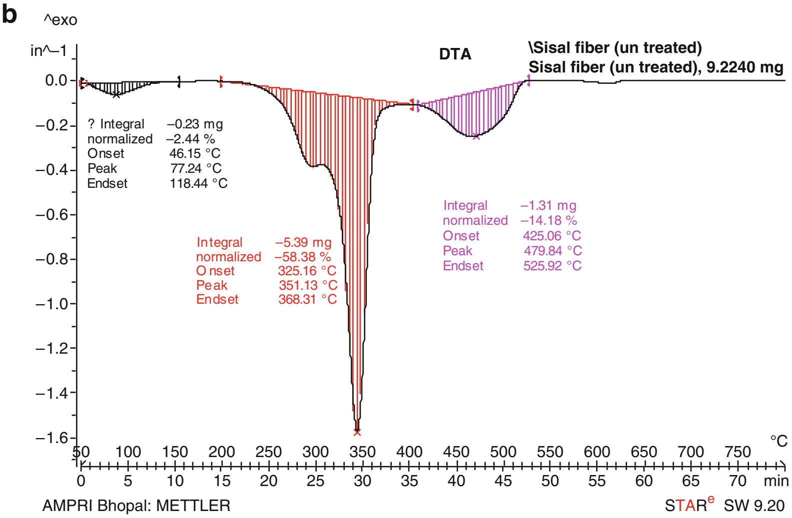
different gauge lengths and the results show that the gauge length does not seem to influence the modulus of the fiber. The variability in modulus, for a given gauge length, is likely due to the variability in the microstructure of the sisal fiber and possible damage that occurred during the extraction process [84]. Over the last few decades, several studies have been reported on the use of sisal fiber as reinforcements in polymer matrices [85–91]. Due to various advantages the use of sisal fiber and its composites is becoming a great area of interest amongst scientists and engineers.

Thermal Properties

The thermal property of sisal fiber was studied at AMPRI Bhopal using the Mettler Toledo STAR^{e} System by thermo gravimetric curve and differential thermo gravimetric curve, as shown in Fig. 22.6a, b. The temperature range used for analysis was from 500°C to 800°C. Results revealed that in the temperature range of 50°C–200°C, dehydration as well as degradation of lignin occurred. But, at



TGA Curve of untreated sisal fibre



DTA Curve of untreated sisal fibre

Fig. 22.6 Thermal properties (**a**) TGA (**b**) DTA of untreated sisal fiber

350°C most of the cellulose decomposed and released energy, which is shown in the Differential Scanning Calorimetry (DSC) curves. In the DTA curves, the peak observed at 78°C for sisal fiber corresponds to the heat of evaporation of water from the fiber (stage 1). The second peak of sisal at about 350°C was due to the thermal depolymerization of the hemicellulose and the cleavage of the glycosidic linkage of cellulose (stage 2). The third peak (at about 450°C) for sisal fiber may be due to the further breakage of the decomposition products of stage 2.

Earlier, Yi et al. studied the thermal properties of sisal fiber by thermo gravimetric curves and thermo gravimetric differential curves in thermal process. The temperature used for the analysis by this author was 30–600°C. It is reported that dehydration as well as degradation of lignin occurs in the temperature range from 60 to 200°C. As reported in the present study carried out by AMPRI, Bhopal, almost similar thermal properties of sisal fiber were recorded [92, 151].

Comparison of Sisal Fiber with Other Natural Fiber

The density of sisal fiber varies from 1.35 to 1.45 g/cm^2. Literature shows that sisal fiber exhibits tensile strength in the range of 400–700 MPa, which is nearly similar to many commercially used natural fiber such as jute, flax, banana, and sun hemp. Therefore, we can use sisal for commercial application as we can use jute, flax, banana, pineapple leaf fiber, etc. The mechanical properties of some of the natural fibers and other mineral fibers are shown in Table 22.4.

It is evident from Table 22.4 that flax fiber demonstrates higher tensile strength and modulus than sisal fiber due to its smaller lumen and smaller micro fibril angle. A literature review showed that there are large variations in both Young's modulus and tensile strengths of sisal fibre [20, 21, 53, 58, 59, 86]. This variation is due to various factors including the methods of testing. Mukherjee and Satyanarayana showed that different fiber test lengths and strain rates result in different tensile properties for sisal fibers. Increased test length decreases the strength of the fibers because the number of defects is increased. It was also observed that the strength of natural/sisal fibers is not uniform along the length of the fiber bundle. The reason is that the probability of finding significant defects is much larger in a natural/sisal technical fiber than in a single fiber. In addition, the load distribution is much more inhomogeneous in technical fiber [9].

In India, a wide variety of natural fibers is available such as sisal, coir, jute, banana, and sun hemp. These fibers are either the primary products of cultivation such as jute and sun hemp or the byproducts of crops raised for other purposes such as banana and coconut. However, sisal is not cultivated commercially in India. In recent years, considerable developmental activities in the science and technology of composite materials have been undertaken. Polymer matrix composites reinforced with glass fiber, carbon fiber, kevlar fiber, etc. have been among the forefront in the development and are already well-established materials. It is a well-known fact that composite materials offer many advantages over the use of conventional materials. In India, fiber-reinforced composite materials invaded the building construction area and started establishing itself in the mid 1980s in the form of natural fiber composites. The Advanced Materials and Processes Research Institute, CSIR, Bhopal had started its activities in the area of natural fiber composites and now this has grown exponentially in other laboratories and industries.

Natural fibers such as sisal, coir, jute, banana and sun hemp are vital renewable resources that can be used in many applications. Natural fibers are cheaper and easily available resources. As compared to manmade fibers, natural fibers have low specific

Table 22.4 Physico-chemical and mechanical properties of different fibers

Fiber	Density	Cellulose (%)	Hemi cellulose (%)	Lignin (%)	Moisture content (%)	Ash (%)	Micro fibriller angle(ɵ)	Wax (%)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Reference
Sisal	–	67–78	10.0–14.2	8.0–11.0	11.0	–	20.0	–	468–640	9.4–22	3–7	Bismarck et al. [93]
	–	–	–	–	–	–	–	–	568–640	–	3–7	Geoarge et al. [4]
Coir	–	36–43	0.15–0.25	41– 45	8.0		41–45	–	131–175	–	15–40	Bismarck et al. [93]
Oil Palm	–	65	19	–	–	2	46	–	248	6.7	14	Bismarck et al. [93]
Jute	1.3 – 1.46	61–71	13.6–20.4	12–13	12.6	–	8.0	0.5	393–800	10–30	1.5 –1.8	Bogoeva-Gaceva et al. [94]
	–	–	–	–	–	–	–	–	226	–	1.3	Geoarge et al. [4]
Cotton	1.5	82.7	5.7	–	–	–	0.6	–	287–597	–	7.0–8.0	Bogoeva-Gaceva et al. [94]
	–	–	–	–	–	–	–	–	200–400	–	6 –7	Geoarge et al. [4]
Flax	1.4–1.5	71–78	18.6–20.6	2.2	10.0	1.5	10.0	1.7	345–1,500	–	2.7–3.2	Bogoeva-Gaceva et al. [94]
	14–1.5	–	–	–	–	–	–	–	600–1,100	45 –100	1.5–2.4	Li et al. [76]
	–	–	–	–	–	–	–	–	780	–	2–4	Geoarge et al. [4]
Hemp	1.48	70.2–74.2	17.9–22.4	3.7– 5.7	10.8	2.6	6.2	0.8	270–900	–	2.7–3.2	Bogoeva-Gaceva et al. [94]
Bamboo	0.8	–	–	–	–	–	–	–	391–100	48–89	–	Bogoeva-Gaceva et al. [94]
Soft wood	1.5	–	–	–	–	–	–	–	10,000	400	–	Bogoeva-Gaceva et al. [94]
Ramie	1.5	–	–	–	–	–	–	–	400–938	44–128	–	Bogoeva-Gaceva et al. [94]
Banana	1.350	63–64	19	5	10–11		11	–	559 ± 6.7	20	5–6	Idicula and Boudenne [80]
	–	–	–	–	–	–	–	–	54–754	–	1–4	Geoarge et al. [4]
Pineapple leaf fibre (PALF)	1.526	81	–	12.7	13.5		14	–	413+8	–	3–4	Idicula and Boudenne [80]
	–	–	–	–	–	–	–	–	413–1,627	–	0.8–1	Geoarge et al. [4]
Aramide	–	–	–	–	–	–	–	–	3,000–3,150	–	3.3–3.7	Geoarge et al. [4]
Abaca	–	–	–	–	–	–	–	–	756	31.1	2.9	Geoarge et al. [4]
Sun hemp	–	–	–	–	–	–	–	–	760	–	2–4	Geoarge et al. [4]
Glass	2.56	–	–	–	–	–	–	–	2,000–3,400	–	1.8–3.2	Li et al. [76]
	1.5 ± 5.8	–	–	–	–	–	–	–	2,500 ± 8	56–72	3	Idicula and Boudenne [80]
Carbon	–	–	–	–	–	–	–	–	4,000	230–240	1.4–1.8	Shibata et al. [95]

weight and thus higher specific strength and stiffness, their extraction requires less energy, and also their thermal recycling is possible and they have good thermal and acoustic insulating properties. Universally, the demand for natural fibers is increasing day by day. The properties of natural fibers not only provide environmental benefits, but there are other price and physical advantages over synthetic alternatives. Intensive efforts are being made worldwide for the development of natural fiber-based composites for various applications. Advanced composites are used as primary load carrying structural elements, as they are lightweight and result in higher stiffness. Therefore there is a need for understanding the full characteristics of different natural and manmade fibers as they exhibit significant variation in their properties and possess a huge potential to be used in a variety of applications.

22.5 Sisal Fiber Reinforced Polymer Composite

Natural fibers are preferred to synthetic fiber in composites because of the many benefits of the latter: it requires less energy for fiber processing, it is a nonhazardous, replenishable resource, is biodegradable, and has low density and high specific strength, and is cost effective. As plant fibers are hydrophilic, the adhesion between the fibers and hydrophobic polymer matrices is not adequate. To achieve sufficient interfacial bonding, either surface modification of the fiber or plasticization of the fibers is required [18, 58, 59, 96].

The matrices used in sisal fiber-reinforced composites include thermoplastics (polyethylene, polypropylene, polystyrene, PVC, etc.), thermosets (epoxy, polyester, and phenol–formaldehyde resin, etc.), rubber (natural rubber, styrene-buta-diene rubber, etc.) gypsum, and cement. The effects of fiber length, fiber orientation, processing methods, fiber volume fraction and fiber surface treatment on the mechanical and physical properties of sisal fiber reinforced composites have been studied.

22.5.1 Natural Fiber Reinforced Polymer Composite

Sisal fiber can be added as reinforcement in thermosets, thermoplastics, rubbers, cement, and gypsum and their composites are similarly classified as thermosets, thermoplastics, rubbers, and cement and gypsum according to their matrices.

22.5.2 Fiber Matrix Adhesion in Natural Fiber Reinforced Polymer Composite

Fiber matrix adhesion refers to the extent of bonding and anchoring between fiber and matrix. The presence of a large number of hydroxyl groups is responsible for the hydrophilic nature of sisal fiber. Several fiber surface-treatment methods have been studied to improve the adhesion properties between sisal fibers and the surrounding matrix and to simultaneously reduce water absorption.

22.5.3 Making of Sisal Fiber Reinforced Polymer Composite

Applications of reinforced composites vary with the methodology adopted for manufacturing. The method of production also affects the cost of the product. As glass fiber-reinforced composites are made by various methods, similarly sisal fiber (natural fiber)-reinforced composites can be manufactured by hand lay-up/spray-up, resin transfer molding (RTM), compression molding, injection molding, filament winding, and pultrusion [81–83, 97]. Each processing method is described here in brief.

1. *Hand Lay-up/Spray up*: Spray up and open contact molding (hand lay-up) in one-sided molds is one of the cheapest and most common process for making fiber composite products. Typical products are boat hulls and decks, truck cabs and fenders. In a typical open mold application, the mold is first waxed and sprayed with gel coat and cured in a heated oven at about 49°C. In the spray up process, after the gel coat is cured, catalyzed resin (usually polyester or vinyl ester at 500–1,000 cP viscosity) is sprayed into the mold, along with chopped fiber. A secondary spray up layer imbeds the core between the laminates (sandwich construction). Then it is cured, cooled, and removed from the reusable mold. In hand layup processing, continuous fiber strand mat and other fabrics such as woven roving are manually placed in the mold. Each ply is sprayed with catalyzed resin (1,000–1,500 cP) and the resin is worked into the fiber with brush rollers to wet-out and compact the laminate.
2. *Resin Transfer Molding* (*RTM*): The RTM system gives high quality surface on both the sides. A relatively low pressure (vacuum to 100 psi) process, RTM makes perfect shapes in 30 min to 1 h. The fabricator generally gel coats one or both mold halves, then lays continuous or chopped strand mat and the core, if used, into the bottom half, and closes the mold. The resin transfers into the mold through injection pressure, vacuum pressure, or both. Cure temperature depends on the resin system used. Heater blankets can heat the mold up to 202°C, if the matrix allows sensors to detect resin flow position in the mold and monitor resin and cure data [98].
3. *Compression Molding*: Compression molding is a molding technique for making composite materials under specific temperature and pressure. The unit cost is reduced by the faster cycle times that are possible when compression molding/sheet molding compounds (SMC) are made. SMC is a sheet that sandwiches chopped fiber between two layers of resin paste. Chopped fiber drop onto the paste and a second film carrier faces another layer of resin down on top of the fiber. Rollers compact the sheet to saturate the fiber with resin and to squeeze out

entrapped air. When the SMC is ready for molding, it is cut into sheets and is assembled on a mold with the required temperature. The mold is closed, clamped, and between 500 and 1,200 psi pressure is applied. Material viscosity drops and the SMC flows to fill the mold cavity. After curing, the mold is opened and the component removed manually or through an integral injector system.

4. *Injection Molding*: Automated injection molding of thermoset bulk molding compound (BMC) has increasingly taken over markets previously held by thermoplastics for application in electrical and automotive components, housing appliances, and motor parts. BMC is a low-profile (nearly zero shrinkage) formulation of a thermoset resin mix with 15–20% chopped fiber. Injection molding is a fast, high volume, low pressure, and closed process. Injection speeds are typically 1–5 s and nearly 2,000 small parts can be produced per hour. A ram or screw type plunger forces a material shot through the machine's heated barrel and injects it into a closed, heated mold. Heat build-up is carefully controlled to minimize curing time. After cure and injection, parts need only minimal finishing [99].
5. *Filament Winding*: Filament winding is an automated, high volume process that is ideal for manufacturing pipe, tank, shafts and tubing, pressure vessels, and other cylindrical shapes. The winding machine pulls dry fibers from supply racks through a resin bath and winds the wet fiber around a mandrel.
6. *Pultrusion*: Pultrusion is the continuous, automated closed-molding process that is cost effective for high volume production of constant cross sectional parts. Pultruded custom profiles include standard shapes such as channels, angles, beams, rods, bars, tubing and sheets.

Sisal Fiber-Reinforced Thermoset Polymer Composite

Thermoset composites are made up of thermoset resin-like polyester; epoxy and phenol–formaldehyde resin composites with varying fiber volume fractions and fiber length were prepared by following one of the techniques. Among polyester epoxy and phenol–formaldehyde composites, a phenolic-type resin performed as a better matrix than epoxy and polyester resins with respect to tensile and flexural properties due to the high interfacial bonding in phenolic composites [58, 59, 100].

In natural fiber composites, polyester is the most widely used thermosetting polymer with natural fiber. Irrespective of fiber length, the compression molding method is the most widely used and most convenient method to make these composites.

Physical and Mechanical Properties of Sisal Fiber-Reinforced Thermoset Polymer Composite

Variation in tensile, impact, and flexural properties of thermoset composites, viz. sisal–polyester, sisal–epoxy, and sisal–phenol–formaldehyde is explained here, with the change in length of the fiber (5–30 mm), fiber volume, etc.

Sisal Fiber-Reinforced Epoxy Composites

Considerable work has been done on the sisal fiber-reinforced epoxy composites. It is reported that the fractured cross sections of the sisal–epoxy composites, showed no epoxy resin in the fiber lumen. The total lumen area in the fiber cross-section was found to be 15% and the total void content was about 17%. In sisal, total leaf mass contains only 2–4% sisal fibers; other cells take care of the water distribution. Oksman et al. [9] studied the thermoplastic fiber composites and showed that lumen was filled with the polymer matrix. Fibers therefore have distribution channels between the single wood cells. It is possible that the absence of such channels in sisal, due to the different function of sisal fibers, is the reason for lack of polymer in the lumen. At several locations in the sisal fiber, a gap between the fiber and matrix can be observed. The gaps indicate weak fiber–matrix adhesion [9, 58, 59].

Mechanical Properties of Sisal Fiber-Reinforced Epoxy Composites

Earlier work showed that sisal fibers incorporation significantly increased the tensile strength and Young's modulus of the epoxy resin; a composite with 46% by volume of sisal fibers has a Young's modulus of about 20 GPa. The tensile strength of the same material is 210 MPa. Moreover, Bisanda and Ansell [86] reported that the flexural modulus for unidirectional sisal epoxy composites showed 16 GPa at 40% fiber volume. The flexural strength was 266 MPa [9].

The tensile modulus of sisal fiber was 24 GPa. The tensile modulus of the sisal fiber made from the bundles of technical fibers was found to be lower than the real fiber (single fibril) since the individual fibrils are not loaded uniformly. The effective fiber modulus in the composite was 40 GPa. This point demonstrates a more favorable stress distribution in the sisal fibers in the composite material.

Oksman et al. [9] assumed that all fiber fracture happens at the same critical stress and this corresponds to the final fracture. For volume fraction of fiber 0.28, 0.35, and 0.46, the effective fiber strength obtained was 420, 400, and 390 MPa respectively. Effective fiber strength around 400 MPa was also reasonably compared with measured average fiber strength of 550 MPa. The earlier researchers recorded that poor interfacial adhesion leads to fiber–matrix debonding close to fracture sites and corresponding load redistribution from fractured fibers to neighboring fibers. The results from mechanical testing demonstrate that sisal fiber shows higher modulus when embedded in a matrix material as compared to a material without matrix. On the other hand, the effective fiber strength in the composite is lower than the measured fiber strength. This indicates that the low strength fraction of the fiber population controls composite strength. However, more uniform fiber distribution and improved fiber–matrix adhesion may improve the strength of sisal–epoxy composites [9].

In a natural fiber polymer composite, natural fiber is incorporated in a definite volume in the polymer matrix. Mechanical properties can be enhanced by increasing the fiber volume in a composite, but after a certain level, it may start decreasing due to the poor bonding between fiber and matrix. Oksman et al. [9] studied the effect of fiber loading with epoxy polymer. As shown in the Table 22.5, sisal fiber

Table 22.5 Effect of fiber loading on tensile properties of sisal fiber reinforced epoxy thermoset composite

S. No.	Fiber volume (wt%)	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Reference
1.	0	1.15	76	3.10–3.20	7.3	Oksman et al. [9]
2.	28	1.16	169 ± 23	14.2 ± 1.6	2.3	
3.	35	1.17	183 ± 16	14.5 ± 1.6	2.2	
4.	46	1.17	211 ± 12	19.7 ± 1.5	1.9	

significantly increased the tensile strength and Young's modulus of the epoxy resin. The composite with 46% by sisal fiber volume has a Young's modulus 20 GPa and a tensile strength of 210 MPa. But Bisanda and Ansell [86] attained a flexural strength about 266 MPa. In general, the mechanical properties of thermoset composites increased with the fiber length. It is interesting to note that at a fiber length of 5 mm, the tensile and flexural properties of phenolic composites was about 20% higher than those of epoxy composites. But by increasing the length of the fiber from 5 to 20 mm, the tensile and flexural strength of the epoxy resin composite are increased as compared to other composites. Polyester composites did not show any significant enhancement in its tensile and flexural strength with the change in fiber length in the range of 5–30 mm. It can be noticed that the mechanical properties of epoxy polyester composites showed a marginal decrease with an increase of fiber length from 20 to 30 mm [58, 59].

Sisal Fiber-Reinforced Polyester Composite

The tensile and flexural behavior of sisal fiber-reinforced polyester composites were investigated as a function of fiber length and fiber content by Sreekumar et al. [101]. Resin transfer molding and compression molding techniques were used for composite making. From the studies, it was found that mechanical properties increased with an increase in fiber loading in both cases [101].

Tensile and Impact Strength

Neat polyester composite showed tensile strength around 41 MPa, Young's modulus around 9.68 GPa, and flexural strength around 61 MPa. After reinforcement with fiber, mechanical properties were enhanced and some of the important properties are explained below. Singh et al. [102] reported that sisal–polyester composites from nonwoven sisal mats with fiber content 50% by volume showed a tensile strength of 30 MPa and a tensile modulus of 1.15 GPa. The composites were manufactured by impregnation of the nonwoven sisal mats under compression molding for 2 hrs [9, 102].

Effect of Fiber Length

Results showed that tensile strength and Young's modulus increased with increase in fiber length which was maximum at fiber length of 30 mm. On further increasing the fiber length, the strength reduced. Thus, fiber having length of

5–30 mm was found to be suitable for effective reinforcement in polyester composites [101].

Effect of Fiber Loading

As fiber volume increased, tensile strength and Young's modulus for the composite also increased up to a fiber loading of 42–43% volume fraction, respectively, but after that a decreasing trend in properties was reported [101]. This may be due to the higher fiber volume because there is a strong tendency for fiber–fiber interaction at lower fiber loading, dispersion of fiber is very poor and thus stress transfer may also be poor. In sisal fiber-reinforced polyester composite, therefore, both lower fiber volume and higher fiber volume are responsible for downright properties because of poor wetting and dispersion of fiber [101].

Mishra et al. [46] studied the effect of fiber volume on different mechanical properties of sisal–polyester composite. They found that while increasing fiber volume up to 30%, the tensile, flexural, and impact properties increased, but on further increment in fiber volume, they showed unqualified properties. Addition of 30 wt% fiber increased the tensile and flexural strength of composite to about 198% and 122% compared to that of neat polyester composite. Like tensile and flexural strength, impact strength also increased while loading fiber volume up to 30%, as shown in Table 22.6, but after increasing fiber loading, there was a downfall in the impact properties by about 46% as compared to 30% wt fiber content composite. This may be due to less fiber–matrix interaction. At high ratio of fiber in the composite, polymer would infiltrate it poorly [46].

Flexural Properties

It is observed that flexural strength and flexural modulus increased with increase in fiber length. Composites having fiber length 30 mm showed a maximum flexural strength and flexural modulus; beyond that limit a decreasing trend was observed [101].

Water Absorption

The slightest amount of water can significantly affect the mechanical properties of natural fiber-reinforced composites. Water absorption in a fibrous composite is dependent on many factors such as temperature, fiber loading, orientation of fibers, permeability of fibers, surface protection, area of the exposed surfaces, diffusivity, void content, hydrophilicity of the individual components, etc.

Table 22.6 Effect of fiber loading on impact properties of sisal fiber reinforced polyester composite

S. No.	Fiber volume (wt%)	Impact strength (J/m)	References
1.	0	14.76	Mishra et al. [46]
2.	10	76.52	
3.	20	109.19	
4.	30	163.58	
5.	40	88.23	
6.	30	261	Present study by authors

The neat polyester resin showed very low water uptake due to the three dimensionally cross-linked network structure after curing. The –OH group in the chain end of polyester and oxygen of the ester linkage influences the formation of hydrogen bonds. However it absorbs 0.05 mol% of water due to the presence of micro cracks and also due to the hydrophilic nature of polyester. The fiber-reinforced composites absorb water very rapidly at the initial stage and later a saturation level is attained, and there is no further increase in water absorption. As the fiber content increased the water absorption also increased due to the hydrophilic nature of the fiber [101].

Sisal Fiber-Reinforced Urea–Formaldehyde Composite

Urea–formaldehyde resins (UFR) are the most prominent examples of the class of thermosetting resins usually referred to as amino resins. There are various advantages to the use of UFR, including low cost, ease of use under a wide variety of curing conditions, low cure temperatures, water solubility, resistance to micro organisms and to abrasion, hardness, excellent thermal properties, etc.

Impact Strength

The impact properties of composite materials are directly related to its overall toughness. The impact strength of sisal-reinforced urea–formaldehyde composite with 30 wt% sisal fiber is 5.78 KJ/m^2. While increasing the sisal fiber loading from 30 to 50 wt%, the impact strength increased by 62.98% but on further increasing sisal fiber volume up to 60 wt%, the impact strength decreased [103]. Composites with 50 wt% fiber volume showed higher strength which may be due to the proper interfacial adhesion between the fiber and matrix; the fibers with desired quantity act as better stress transferring media. In addition, the interspaces and stress concentrations shoot up with the increase of the sisal fiber. These fibers could have acted as crack initiation points during impact. Therefore, inferior impact strength was obtained in the composite containing 60 wt% sisal fiber [103].

Flexural Property

It is observed from the work done by earlier researchers (Table 22.7) that sisal-reinforced urea–formaldehyde composite with fiber volume 30 wt%, showed higher flexural strength (58.58 MPa) and on further increasing the fiber volume from 30 to 70 wt%, the flexural strength decreased from 58.58 to 15.28 MPa. Meanwhile, the flexural modulus decreased from 7.63 to 1.59 GPa [103].

Table 22.7 Flexural properties of sisal fiber–urea formaldehyde composite

S. No.	Fiber volume (%)	Density (g/cm^3)	Flexural strength (MPa)	Flexural modulus (GPa)	Specific strength (MPa.cm^3/g)	Specific modulus (GPa.cm^3/g)	Reference
1.	30	1.53	58.58	7.63	38.29	4.99	Zhong et al. [103]
2.	40	1.52	55.80	5.27	36.71	3.47	
3.	50	1.48	53.07	4.93	35.86	3.33	
4.	60	1.44	37.73	4.09	26.20	2.84	
5.	70	1.22	15.28	1.59	12.52	1.31	

Water Absorption Property

Rong et al. [38] reported that the water absorption of composite with 30 wt% sisal fiber was only 0.98%. This may be because of the greater adhesion between the fiber and matrix and the low water absorption nature of the matrix. It was observed that with an increase in sisal fiber content from 30 to 70 wt%, water absorption increased. This might be because of the poor distribution of fibers in the composite, which converts into lumps of fiber. These lumps require more force to deform during hot pressing, and as a result more stresses might have got incorporated in the composites. When the composites were tested for water absorption, a greater proportion of these stresses was released, causing high water absorption. It is evident that because of its hydrophilic nature, sisal fiber absorbs moisture readily [103].

Thus, it is concluded that fiber as a filler in a matrix enhances the mechanical properties because sisal has high tensile properties and its composite have high strength to weight ratio.

Fiber Matrix Interphase Adhesion

The mechanical properties of fiber-reinforced polymer composites are controlled by factors such as nature of matrix, fiber–matrix interface, fiber volume or weight fraction, fiber aspect ratio, etc. Due to the hydrophilic nature, the fibers pulled out from polyester and polyethylene matrices, they were compared with the fibers pulled out from the epoxy matrix, which carry polymer particles on their surfaces. On the other hand, fracture of the fibers occurs at the crack plane in phenolic composites. From SEM microstructures of different composites, it was observed that the bonding of sisal fiber with the four matrices are found to be in the order of phenolic > epoxy > polyester > polyethylene [58, 59].

From SEM studies, it can be observed that the untreated sisal fiber has a network structure and includes waxes and other low molar mass impurities whereas sisal fiber gets thinner after treatment. It is possible that treatment leads to microfiber fibrillation. The surfaces of the treated sisal fiber become smoother as compared to those of untreated sisal fiber. The effective surface area of fiber available for contact with the matrix also increases in composites while also reducing the diameter of sisal fibers and thereby increasing their aspect ratio. This may offer better fiber–matrix interface adhesion and improve stress transfer. These will give rise to improvement in mechanical properties [78].

Chemical Modification and its Effect on Fiber Matrix Adhesion

To modify the fiber surface and its internal structure, various treatments were done, and when the treated fibers were incorporated into the matrix, treatments showed two types of importance related to interface: one between fiber bundles and the matrix and the other between the ultimate cells. In general, fiber treatments can increase interphase adhesion and also lead to penetration of the matrix resin into the fibers, thereby influencing the mechanical properties of fiber and composites, which are illustrated here.

Treatment of sisal fiber with alkali for making composites to increase interfacial adhesion is very common, but extent of effect is determined on the basis of quantity and duration of treatment. Alkali treatment makes the sisal fiber surface rougher by removing the waxy materials. The rough surface produced on the sisal fiber leads to better mechanical anchoring with the matrix [34].

The surface modification process usually affects the morphology, mechanical properties, and thermal degradation of natural fiber. Alkali treatment improves the surface structure of sisal fiber and decreases the diameter of fiber. Due to the removal of cementing substances on the inner surface of lumen, polymer can easily penetrate into the cavities of sisal fiber. Moreover, alkali treatment increases the numbers of possible reactive sites and allows better fiber wetting. Sisal fiber surface was wrapped with some cementing substances before alkali treatment, which made the epidermal cells of sisal fiber combine with neighboring cells closely. The alkali reagent has an effect on the chemical composition of the fiber, the degree of polymerization, and the molecular orientation of the cellulose crystallite due to cementing substances such as lignin and hemicelluloses that were removed during the treatment process. TGA studies showed that in the untreated fibers, degradation temperature is 355°C while after mercerization of fibers it is 377°C means thermal stability increased after treatment [78].

In permanganate treatment for increasing the adhesion between sisal fiber and polymer, acetone solution of $KMnO_4$ is used to induce grafting of polymer on to sisal fibers. Here MnO_4^- ion is responsible for initiating permanganate induced grafting. These chemical modifications increased the viscosity of the hybrid composites because of the increased fiber–matrix interaction [35].

In stearic acid treatment, solution of stearic acid is used to induce interfacial adhesion of the sisal fiber. It was found that due to the presence of hydroxyl groups on the sisal fiber, stearic acid enhanced the viscosity of the hybrid composite [35].

In silane treatment, the level of fiber matrix adhesion is further enhanced by the presence of a silane coupling agent. The interfacial shear strength between natural fiber and matrix improved by morphological modification of the fiber surface. Fiber surface silanization results in improving the wetting of fiber. The reduction of the hydrophilic tendency of sisal fiber due to the treatments and the reduction of moisture absorption obtained with silane treatment can be associated with the interpenetration of the coupling agent into the cell wall of the fibers through its pores and its deposition in the interfibrillar region, generating a barrier that binds the moisture access to fibers [39].

In peroxide treatment, peroxides were added to a molten mass of the polymer at the time of mixing with fibers. After treatment, the peroxide-treated composites showed higher viscosity than untreated composites because of the grafting of polymer on the sisal fiber surface in the presence of peroxides [104].

In acrylation treatments, fiber densities decreased due to the extraction of soluble products in acrylamide which also affect fiber texture and its dispersion in the resin when manufacturing composites. The SEM of treated and untreated sisal fiber were compared and results showed that *N*-iso propyl-acrylamide 1, 2, and 3% gradually attacks the fiber, exposing its inner layers, and in the case of 3% treatment, significantly altering its surface. The increase of the crystallinity index of acrylamide-treated sisal samples suggests that the acrylamide extracts an amorphous portion (lignin and hemicellulose) of the fibers [35].

In bleaching, untreated fibers were treated in sodium chlorite solution with a liquor ratio of 25:1 and anticolored with 2% solution of sodium sulfite [36, 37].

In cyanoethylation grafting, polyester composites made up of cyano ethylated sisal showed improved mechanical properties as compared to the control. This may be due to bonding of P-cyanoethyl groups of the fiber with the polyester, thereby improving the fiber matrix orientation [36, 37].

The graft copolymerization of acrylnitrile and methylmethacrylate (MMA) onto 5% alkali-treated sisal fiber were carried out at a temperature of 40°C in an aqueous medium to get acrylnitrile-grafted and MMA-grafted sisal fiber with a different percentage of grafting [36, 37].

Physical and Mechanical Properties of Chemically Modified Sisal Fiber-Reinforced Thermoset Polymer Composite

Treatment of natural fiber has been done to improve interfacial adhesion for making sisal-reinforced thermoset polymer composites. Studies were carried out on the properties of fiber with various treatments and the effect of treatment on the polyester composite's mechanical properties (30% fiber volume) [36, 37]. Results from Table 22.8 showed that 5% alkali-treated sisal composite showed enhancement in the impact strength of almost 35 J/m as compared to untreated polyester composite, but an increase in alkali concentration from 5 to 10% resulted in a decrease in the impact strength as compared to 5% alkali-treated composite. Bleached, defatted, and cyanoethylated sisal composite showed almost similar impact strength of 171 J/m, indicating that treatment increases the impact strength of fiber. Cyanoethylation of sisal was done at various temperatures (50°C, 60°C, 70°C); treatment at 60°C cyanoehtylated sisal showed a higher impact strength of 192.46 J/m as compared to cyanoethylated sisal at 50°C or 70°C (171 J/m). An increase from 5 to 10% concentration in acrylonitrile grafting increased tensile strength, but on increasing concentration up to 20% the impact strength fell suddenly [36, 37].

Mishra et al. [36, 37] tested the tensile and impact strength of maleic anhydride-treated sisal composite at different fiber volumes and found that tensile and impact strength decreased gradually from 40% fiber volume composite to 55% fiber volume polyester composite. It was concluded that maleic anhydride-treated composite at fiber volume 40% showed higher and better mechanical properties [36, 37]. Related to tensile properties evaluation, Mishra et al. [36, 37] concluded that a composite of alkali treated (5%) sisal fiber was found to achieve better mechanical properties as compared to untreated, dewaxed, 10% alkali treated and bleached sisal fiber-reinforced composites. A 5% alkali-treated sisal fiber-reinforced composite

Table 22.8 Effect of sisal fiber treatment on different properties of Sisal fiber reinforced polyester thermoset composite

S. No	Treatment	Fiber volume (%)	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (J/m)	Reference
1.	Untreated	30	39.057	52.11	261	Present study by authors
2.	Alkali (5–10% concentration)	30	–	–	167.2–197.8	Mishra et al. [46]
3.	Bleached	30	47.5	112.19	171.17	
4.	Cyanoehtylation (60°C)	30	84.29	149.09	171.27–192.46	
5.	Acrylonitrile grafting (5–10% concentration)	30	–	–	160.27–171.15	
6.	MMA grafted (5–10% concentration)	30	–	–	158.29–169.71	
7.	MMA (methyl-methacrylate) grafted (5% concentration)	–	72.3 ± 4.3	81.2 ± 7.2	–	Bismarck et al. [93]

showed enhancement in tensile strength (22%), flexural strength (43%), and impact strength (21%) as compared to the untreated composite. This increase can be attributed to fibrillation, which means a breaking down of fiber bundles into smaller fibers and thereby increasing the effective surface area for matrix adhesion. At higher alkali concentration treatment, brittleness of fiber increases, which may have resulted in lowering of mechanical properties. The defatted sisal polyester composite showed better mechanical properties because dewaxing of fiber helps in improving fiber–matrix interaction. Delignification occurs in the bleaching process, which results in lowering of tensile strength because lignin acts as a cementing material. After delignification, there is less stiffness and more flexibility in bleached composites, which results in better flexural strength. After delignification, the polyester resin replaces the role of lignin in fiber and interfacial fiber–matrix adhesion increases, which results in high impact strength of the composite [36, 37].

With cyanoethylation, treatment of sisal fiber at 60°C showed higher tensile strength (84.29 MPa) and flexural strength (149.09 MPa) compared with its treatment at 50°C, as shown in Table 22.8. As the temperature increases from 50 to 60°C, the composite showed enhanced mechanical properties, but above 60°C, the values of all properties decreased. With acrylonitrile grafting on sisal, tensile strength increased 1.1% and flexural and impact strength decreased 5.1% and 2%, respectively. But an increase in grafting percentage up to 10%, increased the tensile strength, flexural strength, and impact strength by about 10.3%, 25.8%, and 4.6%, respectively [36, 37].

The impact strength of methyl-methacrylate (MMA)-grafted (5%) sisal fiber composites was found to be 158.29 J/m. However, composites produced from 10% MMA grafted sisal fiber showed high tensile strength, flexural strength, and impact strength of 7%, 13.3%, and 2.7%, respectively [36, 37]. In fact, an increase in MMA concentration up to 20% reduced the impact strength [36, 37]. A comparison of the result of tests done on fiber grafted with acrylonitrile and MMA shows that acrylonitrile grafting is better than MMA-grafting. At a higher percentage of grafting, fiber becomes porous, which results in lower values. The variation in the impact strength explains why there is no significant variation in results between different concentrations of treatment of MMA. However, the work done at AMPRI shows the impact properties of neat polyester composite, sisal-reinforced polyester composite, jute-reinforced fly ash polyester composite, and jute-reinforced red mud polyester composite showed an impact strength of 2,250 J/m^2, 3,600 J/m^2, 2,660 J/m^2, 4,560 J/m^2, respectively. Results showed that the impact strength increased predominantly by reinforcing the polymer with sisal fiber.

22.5.3.1 Sisal Fiber-Reinforced Thermoplastic Polymer Composite

Thermoplastic resin softens when heated, hardens when cooled, and allows for reprocessing and remelting without any chemical structure or properties. Thermosets are plastics that cannot be melted once cured and include resins such as epoxies; considerable interest has been generated in the manufacture of thermoplastic composites due to their unique properties, such as high strength to weight ratio, good dimensional stability, good fracture toughness, scratch resistance, thermal stability, and good resistance against chemicals [105, 106]. With more stringent demands for recycling, standard thermoplastic polymers are being used as substitutes for thermosetting polymers as matrix materials for high-volume consumer-driven composites. Natural fiber thermoplastic composites have been used for applications such as transportation, manufacturing of sporting goods, packaging, and similar industries because they are reusable, reshapable, and repairable; the composites are ecofriendly as they are developed with renewable material. Thermoplastic resins have some disadvantages in that they are prone to cramp and have poor melt flow characteristics; they degrade at medium and high temperature and for mixing with fiber need to be heated well above the melting point for the polymer to wet the fibers sufficiently [74, 107, 108].

The most commonly used thermoplastic resins are polyethylene (PE), polypropylene (PP), polyether ether ketone (PEEK), polyvinyl chloride (PVC), polystyrene (PS), polyolefin etc., which have been reported as the matrices [76]. Polyethylene is the cheapest and has excellent toughness and impact strength, but the lowest in service temperature. The resin can be used both in virgin and recycled form. All polyethylene grades [i.e., Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE)] are used for the manufacture of thermoplastic composites. PVC is the strongest resin with the highest service temperature, high stiffness capability, mechanical strength, and weather resistance properties. Polyvinyl chloride resins are being used in thermoplastic composites for manufacture of window panels in construction because it is cheap, durable, and easy to assemble [96].

To make natural fiber thermoplastic composites, fiber and thermoplastics resin can be mixed in any one of the two following methods:

(a) Melt mixing
(b) Solution mixing

In melt mixing, the fiber is added to a melt of thermoplastics, and mixing is performed using a mixer at a specified temperature and speed and for a specified time. Then the mix is taken out from the mixer while hot and extruded in the form of long and thick rods using an injection molding machine.

In solution mixing, the fibers are added to a viscous solution of thermoplastics in a solvent in a stainless-steel beaker with a stainless-steel stirrer. The temperature is maintained for some time and the mix is transferred to a flat tray and kept in a vacuum oven to remove the solvent. The solution mixing process avoids fiber damage that normally occurs during blending of fiber and thermoplastics by melt mixing.

Randomly oriented sisal fiber reinforced composites are prepared by standard injection molding of the blends. Oriented sisal composites are processed by aligning the long extruded rods with compression molding [88, 89].

Physical and Mechanical Properties of Sisal Fiber-Reinforced Thermoplastic Polymer Composite

Testing of mechanical properties such as tensile strength (ASTM-D-638), flexural strength (ASTM-D-790), and impact strength (ASTM-D-256) was done following standard methods. The water absorption of both untreated and treated composites was determined as per ASTM-D-570. The variation in tensile, impact, and flexural properties of thermoplastic composites, viz. sisal–polypropylene and sisal polystyrene, is explained here, and the change in fiber volume also given here.

The Effect of Fiber Loading on the Mechanical Properties of Sisal Fiber Thermoplastic Composites

The work done by Mishra and Naik [109] shows that an increase in the fiber volume in the matrix leads to a reduction in the mechanical properties of the composite due to lack of adhesion between fiber and polymer. The grafting of sisal fiber with maleic anhydride resulted in better adhesion with polymer [109]. Antich et al. [110] reported that there was an increase in the Young's modulus with fiber loading, but tensile strength and deformation at break were found to be decreased (Table 22.9). The deformations at break decreased to 3.88% without sisal fiber and 0.97% with 25% sisal fiber as a consequence of the weak fiber–matrix interface derived from the divergent behavior in polarity between the hydrophilic sisal fiber and the hydrophobic polymer matrix [110]. These studies conducted by Sreekumar et al. [111] using wheat flour-based thermoplastic polymer-based sisal fiber composites showed not much increase in the tensile strength; Young's modulus, however, increased. The mechanical properties of composites with varying sisal fiber content were measured and these measurements are shown in Table 22.9 [111].

Table 22.9 Mechanical properties of sisal fiber (Different fiber loading) reinforced thermoplastic composites

S. No.	Composite matrix	Fiber/matrix content (wt%)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (GPa)	Reference
1.	Sisal – PS	0	20.64	1.22	3.35	45.55	3.42	Mishra and Naik [109]
	Sisal – PS	40/60	8.63	1.30	3.30	16.55	3.04	
	Sisal – PS	45/55	6.97	0.90	2.75	19.33	2.90	
	Sisal – PS	50/50	3.30	0.66	2.50	17.21	2.79	
	Sisal – PS	55/45	2.79	0.46	2.00	15.7	2.47	
2.	Sisal – HIPS	0	21.88–22.14	1.84–1.96	3.88–4.04	–	–	Antich et al. [110]
	Sisal – HIPS	5	15.97–17.01	1.94–2.08	1.46–1.68	–	–	
	Sisal – HIPS	10	14.18–14.62	2.22–2.34	1.01–1.11	–	–	
	Sisal – HIPS	15	12.82–13.98	2.43–2.67	0.42–1.3	–	–	
	Sisal – HIPS	20	11.52–11.30	2.22–2.48	0.65–1.27	–	–	
	Sisal – HIPS	25	12.29–10.75	1.87–3.15	0.55–0.97	–	–	
3.	SFR – WFT	0	1.8–2.0	41.2–48.8	31.4–38.6	–	–	Sreekumar et al. [111]
	SFR – WFT	1	1.6–1.8	39.7–46.6	42.7–59.6	–	–	
	SFR – WFT	3	1.5–1.9	44.4–49.6	42.6–43.4	–	–	
	SFR – WFT	5	2.0–2.2	61.0–65.0	36.0–40.0	–	–	
	SFR – WFT	10	1.8–2.2	83.2–102.8	17.2–24.8	–	–	

PS Polystyrene
HIPS High impact polystyrene
SFR-WFT Sisal fiber reinforced wheat flour thermoplastic composites

Studies carried by Leao et al. [28] showed that 70% sisal fiber content in sisal polypropylene composites gave maximum tensile strength and Young's modulus, but flexural strength and flexural modulus property were found to be optimum in 60% sisal fiber, as given in Table 22.10 [28].

The work done by Jarukumjorn and Suppakarn [112] reported that when sisal fiber percentage increased in polypropylene composites the tensile strength increased. Young's modulus, flexural strength, and flexural modulus in polypropylene sisal composites increased by 55%, 9%, and 58%, respectively. But impact strength decreased from 85.80 KJ/m^2 (no sisal fiber) to 12.78 KJ/m^2 (30% sisal fiber) (Table 22.10). The mechanical properties of sisal fiber-reinforced thermoplastic composites under different fiber loading, chemical treatments (alkali, acetylated, stearic acid, permanganate, silane, peroxide, isocyanate, cyanoethylation, benzoylation) and maleic anhydride treatment are shown in Tables 22.11, 22.12, and 22.13, respectively. For better adhesion and improved mechanical strength, Jarukumjorn and Suppakarn [112] used polypropylene grafting with maleic anhydride (PP-g-MA) which resulted in increased tensile strength (23.83–28.66 MPa), Young's modulus (2.11–2.29 GPa), flexural strength (60.88–65.88 MPa), and impact strength (12.78–14.42 KJ/m^2). The increase in the value of these properties was due to covalent linkage formation between maleic anhydride groups and the OH group of the sisal fiber [112]. Further details about the mechanical properties of maleic anhydride-treated sisal fiber composites studied by different researchers are shown in Table 22.13.

Mohanty et al. [105] reported gradual increases in the tensile, flexural, and impact strength of composites. When fiber loading was varied from 10 to 30%, the composites showed increased tensile strength. Tensile strength and flexural strength increased to about 60–70% and 140–150%, respectively. Moreover, impact

Table 22.10 Mechanical properties of sisal fiber (different fiber loading) reinforced polypropylene composites

S. No.	Fiber/matrix content (wt%)	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Impact strength (J/m)	Reference
1.	80/20	11.12	1.25	16.36	1.36	–	Leao et al. [28]
2.	70/30	25.41	2.35	23.76	1.83	–	
3.	60/40	23.25	1.97	32.3	2.78	–	
4.	30/70	23.88	2.11	60.88	3.91	12.78	Jarukumjorn and Suppakarn [112]
5.	0	17.80	–	19.60	–	23.25	
6.	10	24.17	–	34.83	–	40.50	Mohanty et al. [105]
7.	15	26.11	–	46.35	–	46.10	
8.	30	29.25	–	48.96	–	51.79	
9.	45	23.21	–	43.41	–	39.83	
10.	80/20	–	–	49	2.4	19	Oksman et al. [113]
11.	75/25	–	–	45	8	23	
12.	66/34	–	–	46	3.0	27	
13.	63/43	–	–	48	3.6	29	

Table 22.11 Mechanical properties of Sisal fiber (Different fiber loading and orientation) reinforced thermoplastic composites

S. No	Composite matrix	Fiber content (wt%)	Tensile strength (MPa)	Young's modulus (MPa)	Elongation at break (%)	Reference
1.	Sisal – PP (L and R)	0	35.00	498	15.00	Joseph et al. [3]
	Sisal – PP	10	36.00 (29.00)	730 (605)	7.82 (8.00)	
	Sisal – PP	20	39.10 (31.14)	798 (971)	7.11 (8.33)	
	Sisal – PP	30	44.40 (33.84)	1,040 (940)	8.33 (8.50)	
2.	Sisal – PS (L and R)	0	34.90	390	9.00	
	Sisal – PS	10	21.30 (18.16)	629 (516)	9.00 (7.00)	
	Sisal – PS	20	43.20 (25.98)	999 (553)	8.00 (6.00)	
	Sisal – PS	30	45.06 (20.42)	999 (624)	7.00(4.00)	
3.	Sisal – LDPE (L and R)	0	9.20	140	200.00	
	Sisal – LDPE	10	15.61 (10.80)	1,429 (324)	4.00 (27.00)	
	Sisal – LDPE	20	21.66 (12.50)	2,008 (453)	3.00 (10.0)	
	Sisal – LDPE	30	31.12 (14.70)	3,086 (781)	2.00 (7.00)	
4.	Sisal – PS (L)	0	34.9	390	9	Nair et al. [79]
	Sisal – PS	20	43.20	999.9	8	
	Sisal – PS	30	45.06	998	7	

(Properties of randomly orientation of sisal fiber composites are shown in parentheses)
PP Polypropylene
PS Polystyrene
L Longitudinally and *R* randomly oriented solution mixed sisal fiber
LDPE Low density polyethylene

strength increased 23.25 J/m to 51.79 J/m with 10% sisal fiber and 120–125% with 30% sisal fiber [105].

Oksman et al. [113] reported the flexural properties and impact strength of sisal polypropylene (pp) composites with different fiber content. Test results showed that flexural modulus and impact strength increased with increased fiber content but flexural strength was not affected (Table 22.10). Oskman et al. used maleated polypropylene (epolene 43 WAX) as a coupling agent, whereby flexural strength was increased: the flexural modulus of maleated-treated fiber was 4.6 GPa [113].

Joseph et al. [3] worked on sisal thermoplastic composites using three different types of thermoplastic polymer PP (polypropylene), PS (polystyrene), and PE (polyethylene [LDPE]). Joseph et al. [3] reported mechanical properties of sisal thermoplastic composites on the basis of varying fiber loads (0–30%) and orientation (longitudinally and randomly). Joseph et al. [3] found an increase in sisal–PP and sisal–PE composites tensile strength and Young's modulus with an increase in fiber loading, but a decrease in elongation. Sisal–PS composites showed an initial decrease in tensile strength when fiber loading was of 10%, but it increased gradually as the fiber loading went up to 20 and 30% (Table 22.11); flexural

Table 22.12 Tensile properties of treated Sisal fiber thermoplastic composite

S. No	Treatments	Composite	Tensile strength (MPa)	Young's modulus (MPa)	Elongation at break (%)	Reference
1.	Alkali	LDPE Sisal (30/70)	34.27 (31.12)	3,328 (3,086)	1 (2)	Joseph et al. [58, 59]
		SGRP (Sisal/Glass 70/30)	31.26 (27.86)	831.27 (831)	5 (5)	Kalaprasad et al. [114]
		Sisal PP	31.23 (29.55)	–	–	Mohanty et al. [105]
2.	Acetylated	SGRP (Sisal/Glass 70/30)	32.23 (27.86)	919.535 (831)	5 (5)	Kalaprasad et al. [114]
3.	Stearic (4 wt%)	SGRP (Sisal/Glass 70/30)	32.79 (27.86)	1,000.785 (831)	5 (5)	
4.	Permanganate (0.06 wt%)	SGRP (Sisal/Glass 70/30)	32.97 (27.86)	1,081.825 (831)	5 (5)	
		LDPE Sisal (30/70)	38.80 (31.12)	3,816 (3,086)	3 (2)	Joseph et al. [58, 59]
		Sisal – PP (30/70)	45.7 (37)	1,271 (735)	8 (8)	Joseph [115]
5.	Silane	SGRP (Sisal/Glass 70/30)	34.34 (27.86)	1,185 (831)	4 (5)	Kalaprasad et al. [114]
6.	DCP (Peroxide)	SGRP (Sisal/Glass 70/30)	35.03 (27.86)	1,303.7 (831)	4.7 (5)	
		LDPE Sisal (30/70)	41.80 (31.12)	4,156 (3,086)	4 (2)	Joseph et al. [58, 59]
7.	BPO (Peroxide)	SGRP (Sisal/Glass 70/30)	35.77 (27.86)	1,401.75 (831)	5 (5)	Kalaprasad et al. [114]
		LDPE Sisal (30/70)	40.90 (31.12)	4,018 (3,086)	3 (2)	Joseph et al. [58, 59]
8.	Isocyanate	LDPE Sisal (30/70)	41.50 (31.12)	4,068 (3,086)	4 (5)	
9.	Cyanoethylation	Sisal–pp (30%)	35.64 (29.55)	–	–	Mohanty et al. [105]
10.	Benzoylation	Sisal–PP (30/70)	45.8 (37)	1,342 (735)	7 (8)	Joseph [115]
		Sisal–PS (30/70)	48.3 (45.06)	1,125 (998)	8 (7)	Nair et al. [79]

(Properties of untreated composites are shown in parentheses)

SGRP Sisal glass reinforced polypropylene

Table 22.13 Tensile properties of maleic anhydride treated sisal fiber composite

S. No	Composite	Fiber/matrix content (wt%)	Tensile strength (MPa)	Young's modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Reference
1.	Sisal–PS	40/60	9.89 (8.63)	1,705.66 (1,308)	2.75 (3.00)	37.74 (16.55)	4,565 (3,047)	Mishra and Naik [109]
2.	Sisal–PS	45/55	7.65 (6.97)	1,274.91 (900)	3.25 (2.75)	12.73 (19.13)	4,246 (2,896)	
3.	Sisal–PS	50/50	5.51 (3.30)	852.78 (660)	2.75 (2.50)	10.99 (17.21)	3,747 (2,793)	
4.	Sisal–PS	55/45	4.16 (2.79)	555.1 (466)	2.75 (2.00)	18.514 (15.70)	3,217 (2,470)	
5.	SGRP	70/30 (Sisal/Glass)	34.97 (27.86)	1,139.32 (831)	5 (5)	–	–	Kalaprasad and Thomas [34]
6.	Sisal – PP	30/70	45.8 (37)	1,342 (735)	7 (8)	–	–	Joseph [115]

(Properties of untreated composites are shown in parentheses)

strength showed a rapid increase. Joseph et al. [3] observed the mechanical properties in both types of orientation. It was found that the composites containing longitudinally oriented fibers exhibit better mechanical properties than those with randomly oriented fibers. Of all the three types of sisal thermoplastic composites, sisal polypropylene showed the optimum increase in mechanical properties; it was therefore concluded that PP would be a good matrix for sisal polyolefin composites (Table 22.11) [79].

In a natural fiber polymer composite, natural fiber of a definite volume is incorporated in the polymer matrix. Mechanical properties can be enhanced by increasing the fiber volume in composites but once the volume reaches an optimum level, the properties thereafter start to decrease. Nair et al. [79] studied the sisal fiber-reinforced polystyrene composite behavior and they found that tensile strength and Young's modulus increases as a result of the increase in the fiber volume from 0 to 40%, whereas elongation at break decreases on increasing fiber volume. Nair et al. [79] used three different types of orientation: L (longitudinal), T (transverse), and R (randomly); longitudinal orientations gave good mechanical result compared to other orientations (Table 22.11) [79].

An increasing trend in the tensile strength with fiber volume fraction was reported by Joseph et al. [3]. They reported that sisal fiber addition increased the tensile strength from 9 MPa (0% sisal) to 14–15 MPa (30% sisal) and the reinforcement effect largely on matrix ductility, that is, the resistance to crack propagation [3].

Fiber Matrix Interphase

Thermoplastic composite materials frequently showed a lack of fiber matrix adhesion when exposed to adverse/aggressive environmental conditions. Moreover, their composites were prone to swell/warp and shrink when exposed to moist and hot weather conditions. In order to develop composites with better mechanical properties and environmental performance, it is necessary to impart hydrophobicity to the fibers by chemical reaction with suitable coupling agents. This is typically remedied using fiber surface modification. Chemical modification or the addition of a third phase bridging the fiber and matrix phases were successfully applied to improving the interfacial characteristics of many polymer composite systems. Such surface modification of natural fiber would not only decrease moisture absorption, but also increase wet-ability of fibers with resin and improve the interfacial bond strength, which are critical factors for obtaining better mechanical properties of composites. Natural fiber-reinforced thermoplastic composites have poor interfacial bonding between sisal fiber and thermoplastic matrix. To overcome this poor interfacial bonding, a number of fiber pretreatment techniques, such as alkaline treatment, heat treatment, and coupling agent treatment were found to be appropriate [116].

The fiber–matrix interfacial bond strength is expected to be very poor in composites of cellulosic fiber, which is hydrophilic, and thermoplastic polymer, which are hydrophobic in nature. Several treatments have been developed for the above system to improve interface bonding, which improves the mechanical properties and dimensional stability of cellulosic fiber of sisal–LDPE composites [58, 59, 117].

Chemical Modification and its Effect on Fiber Matrix Adhesion

For pretreatment of sisal fiber chemicals such as alkali (NaOH), permanganate ($KMnO_4$), acetylation, peroxide (BPO and DCP), isocyanate treatment, stearic acid, silane, benzoylation [79], maleic anhydride modification, PPG–TDI [34, 60, 61], and cold-plasma treatment are used [76, 118].

It is known that alkali treatment improves the fiber–matrix adhesion due to the removal of natural and artificial impurities from the fiber surface as well as the change in the crystal structure of the cellulose [119]. Moreover, alkali treatment reduces fiber diameter and thereby increases the aspect ratio. Therefore, the development of a rough surface topography and enhancement in aspect ratio offer better fiber–matrix interface adhesion and an increase in mechanical properties was reported by Mohanty et al. [68]. Alkali treatment increases surface roughness resulting in better mechanical interlocking due to the amount of cellulose exposed on the fiber surface [53]. Several other studies were conducted on alkali treatment and the results are discussed elsewhere [36, 37, 41, 86].

To reduce the surface hydrophilicity, the fiber surface is treated with MAPP. The anhydride rings of MAPP covalently link with the hydroxyl groups of the fibers to form an ester linkage. The surface tension of the fiber increases its wettability within the matrix [68].

Fiber modification reduces hydrophilicity of the fiber and improves the physical/chemical interactions between the fiber and polystyrene matrix. The improvement in tensile properties of benzoylated fiber composite is attributed to the presence of a phenyl structure in fiber treated similarly to that of polystyrene, which improves the thermodynamic compatibility between the fiber and polystyrene benzoylated fiber composites. The leach out of alkali-soluble fractions like the waxy layer, lignin, etc., during treatment makes the surface of the fiber very rough and provides better mechanical interlocking with the polymer matrix.

Physico-Mechanical Properties of Chemically Modified Sisal Fiber-Reinforced Thermoplastic Polymer Composite

When a composite is subjected to mechanical forces, the load is transferred between the matrix and the fiber and is governed by the shear deformation of the matrix around the fibers. This shear deformation is produced because of the high Young's modulus of the fiber and the large differences between the mechanical properties of the composite constituents. The mechanical properties of the composites are influenced by component properties, fiber orientation, and fiber–matrix interfacial adhesion.

The interface is a region at least several molecular layers thick with properties intermediate between those of the fiber and matrix phases and arises due to the peculiar restrictions on molecular motions in this zone. Matrix molecules may be anchored to the fiber surface by chemical reaction or adsorption and determine the extent of interfacial adhesion. Fiber modification reduces hydrophilicity of the fiber and improves the physical/chemical interactions between the fiber and matrix. Treatment makes the surface of the fiber very rough and provides better mechanical interlocking with the polymer matrix.

Extensive work was carried out by Joseph et al. on many treatments of natural fiber (alkali, permanganate, peroxide (DCP and BPO), isocyanate) for improving the mechanical properties of sisal fiber LDPE composites. The results showed that in every case the mechanical properties were increased with chemical treatment but peroxide treatment showed the best results (Table 22.12) [58, 59].

Mohanty et al. [105] used 30% sisal fiber with a 6-mm average length of fiber for different types of chemical treatment such as NaOH, cyanoethylation and 2-type maleic anhydride-grafting polypropylene (G-3015) and hostaprime (HC_5). Results showed that the NaOH and cyanoethylation treatments improved the mechanical properties; details are shown in Table 22.12. With the treatment of G-3015 and HC_5, the tensile strength attained was 43.66 MPa and 43.84 MPa, respectively (HC_5), which was higher than that of untreated sisal fiber composites (29.25 MPa). Moreover, with the G-3015 and HC5 treatments results, the flexural strength was 62.42 MPa and 63.66 MPa, respectively, which were found to be higher than the flexural strength of untreated sisal fiber composites (48.96 MPa). The impact strength of sisal fiber composites under different treatments NaOH, cyanoethylation, G-3015, and HC5 were 53.69 J/m, 60.43 J/m, 60.43 J/m, and 81.57 J/m, respectively (The impact strength of untreated sisal fiber composite was 51.79 J/m) [105].

Increase in the surface area of fibre, enhances the fibre matrix adhesion and contributing to the improvement of mechanical properties. Grafting of fiber increases the adhesion property of fiber with matrix and its composites showed improved mechanical properties (Table 22.12) [105].

The work carried out by Kalaprasad and Thomas [34] shows different chemical surface modifications such as alkali, acetic anhydride, stearic acid, permanganate, maleic anhydride, silane, and peroxides improving the interfacial adhesion and compatibility between the fiber and matrix. A polyethylene thermoplastic matrix with sisal and glass hybrid composites was developed. The results showed that in all treatments, tensile strength increased about 10–30% and peroxide treatment showed maximum tensile strength and Young's modulus [34].

Ichazo et al. [120] reported the mechanical properties of treated and untreated sisal fiber. Polyolefin composites were developed using 20% fiber loading. Acetic anhydride was used and acetylated treatment showed an improved tensile modulus by 30–40%. But the impact strength and elongation at break decreased because of the rigid interface between fiber and matrix [120].

22.6 Application of Sisal Fiber-based Composites

Using sisal fiber in composites provides several advantages in terms of product design flexibility, noise absorption, insulation; impact resistance in a crash followed by weight reduction contributes to saving fuel [154].

Sisal fiber has not been optimally utilized and commercially exploited given its abundant availability and good characteristics. Sisal fiber has potential in manufacturing composites that can be used in building materials, automobiles, locomotives, and aerospace applications and it can also replace synthetic fibers such as asbestos and glass fiber in roofing sheets [121]. There is growing interest in the use of sisal fiber due to its high specific strength, significant processing advantages, and low density in composites [122, 123]. In the face of growing industrialization the automotive, packaging, and construction industries, have been forced by the new environmental policies to search for new materials that can substitute for the traditional composite materials consisting of a plastic matrix and inorganic filler as reinforcement matrices. Inorganic fibers have several disadvantages: nonbiodegradability, the abrasion in the processing equipment, and the human health problems associated with operation, processing, and handling of the manmade fibers such as glass, aramid, carbon, and asbestos fibers used in thermoplastic/thermoset composites [104, 124]. However, a major technological gap in sisal technology is the manufacture of the sisal yarn for which the continuous sisal fiber needs to be made and spindling it on bobbins for looming. To achieve this, various techniques such as mechanical extraction of sisal fiber using Raspador machine, softening, sisal yarn-making process, and fabric making using a handloom machine are under progress at AMPRI (CSIR) Bhopal [121].

Sisal is used by industry in three grades (World of Sisal home page 2006). Lower grade fiber is processed by the paper industry because of its high content of cellulose and hemicelluloses. Medium grade fiber is used in the cordage industry for making ropes and baler and binder twine. Whereas ropes and twines are widely employed for marine, agricultural, and general industrial use, high grade fiber is converted after treatment into yarns and used by the carpet industry.

In the ancient period, clay reinforced with straw was used to build walls of dwellings [125, 126]. However, with the development of more durable materials such as metals, the interest in natural materials was lost [125]. In 1941, composites, particularly those based on natural fiber reinforcement received increased attention [41]. Natural fibers were used for making seats, bearings, and fuselages in aircrafts during World War II, which was due to the shortage at that time of aluminum for bearings in ships [127]. However, now attention is given to use natural fiber due to various global environmental threats.

For effective utilization of sisal as reinforcement material, an entire chain-based process is to be followed. This includes the farming, extraction, and processing of fiber, yarn and fabric making, manufacturing of the component, and release of the required product to the user agency/industry. The use of sisal fiber in composites for different applications may follow two different routes, as explained in the flow chart in Fig. 22.7. In the first, the green fiber of the sisal plant is extracted using a mechanical extraction process (Raspador) followed by processing of the fiber. Thereafter two methodologies may be adopted for making the composites. In the first process, fiber will be used for reinforcement in different types of polymer matrices, whereas in the second case, the processed fiber is crimped, by chemical and physical means and the yarn produced mechanically. This yarn, using looms, is converted into fabric to get textile composites for applications such as building, automotive, defense, railways, and geotextiles.

22.6.1 Applications of Sisal Fiber Composites in Building Materials

The traditional building material aggregate such as sand, stone, gravel, cement, steel, brick, block, tiles, paint, and timber have been produced from existing natural resources. Over exploitation of all such building materials leads to environmental damage. Also, due to the high transportation costs of these raw materials and environmental restrictions, there is a mismatch in the demand and supply positions both in rural and urban centers. It is essential, therefore, to find an alternative, a substitute for conventional building materials for the construction industry. Keeping in view the depletion of available natural resources, for instance, deforestation, reduction in availability of fine and coarse aggregates and environmental restrictions, it is necessary to use the available natural resources suitably and develop alternative building materials.

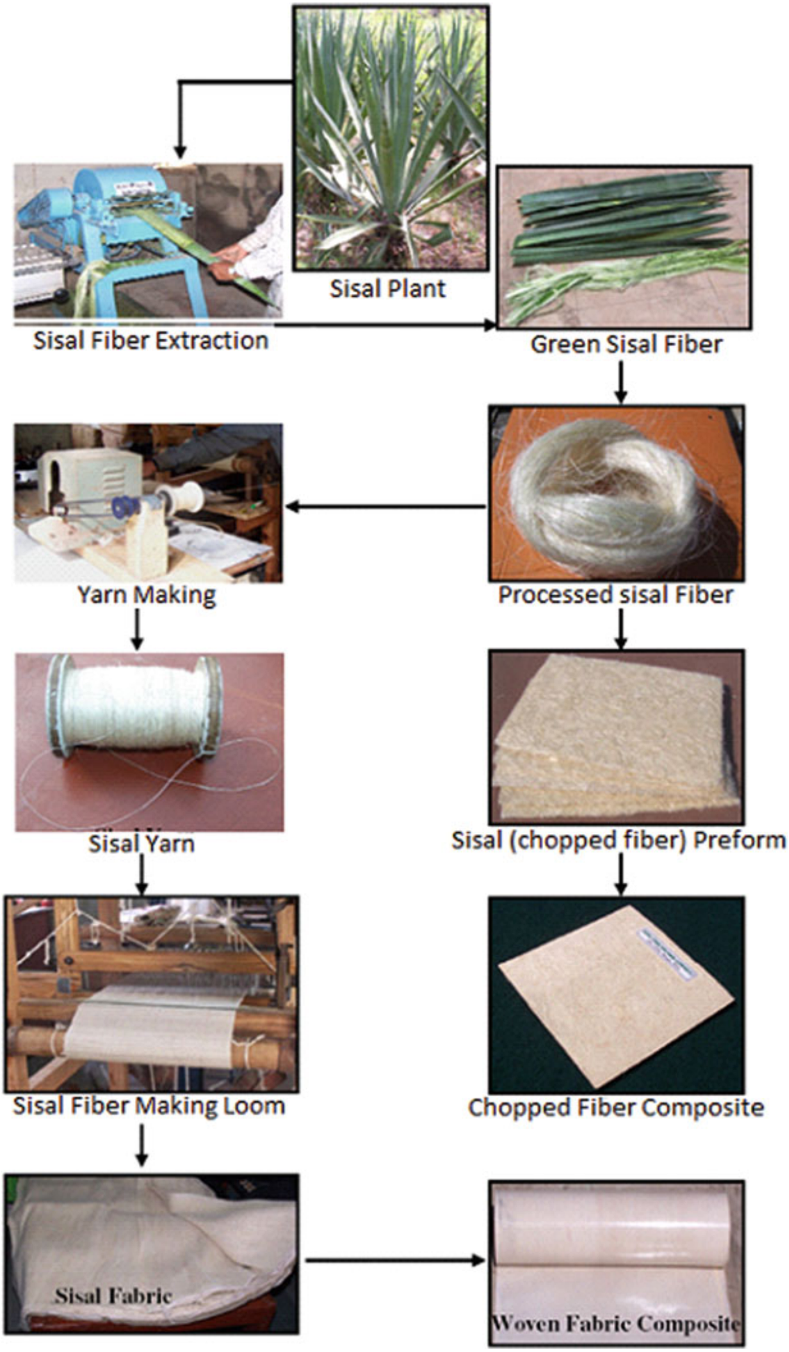


Fig. 22.7 Flow chart for development of Sisal fiber composites

The building industry is under enormous pressure and is unable to meet the demands from different construction sectors. Wood is in short supply, and it is difficult to procure seasoned timber in required quantities. There is a serious need to combat wood scarcity. Existing wood substitutes such as reconstituted panel products: particle/fiber boards, ply wood, and other materials cannot meet the increasing demand for wood without the development of wood substitutes. One important option is to promote development and utilization of natural fibers for the development of composites.

Various attempts have been made recently to rationally utilize abundantly available natural fibers such as jute, sisal, coir, palm, bagasse, and wood fibers in polymer matrices such as polyester, epoxy, and phenolics, to be used as building materials. Developmental work on low-cost building materials based on henequen/palm/sisal fibers and unsaturated polyester resins have been undertaken as a cooperative research project between the government of Mexico and UNIDO [128]. Sisal and coir are one of the most studied fibers, but bamboo, jute, hemp, and grasses have also been studied for making fiber concrete and sheeting materials [129]. The Swedish Cement and Concrete Institute has also been involved with sisal products for many years, especially with respect to research in their durability. Field experience has also been gained by installing sisal fiber-based roofing tiles in South Africa [130]. A new potential application of sisal is for manufacturing corrugated roofing panels that are strong and cheap with good fire resistance [5]. Asbestos fibers are carcinogenic; therefore, sisal fiber cement corrugated roofing sheets are manufactured, which are eco-friendly and an effective alternative to asbestos fiber. Figure 22.8 shows sisal fiber cement corrugated roofing sheet.

Under a mission mode program of AMPRI (CSIR) Bhopal, India, the major tasks involved are exploitation of sisal fiber for engineering applications.

This program is expected to create major employment potential in the rural sector for sisal cultivation; fiber extraction and processing; ropes and cordages; handicrafts; fiber looming; yarn making; carpets and mats; and other value added products.

However, in order to effectively utilize some of the natural fiber as a raw material in developing alternative building materials, the physical–chemical, engineering, mineralogical, and morphological properties of the fiber and other additives have been evaluated at AMPRI Bhopal. Various lab and bench scale experiments were conducted and the process details for commercial scale trials were optimized. In this context, this section of the work addresses the processes and technologies developed at AMPRI Bhopal for large-scale utilization of jute fiber – industrial waste in building materials, wood substitute products, and sisal fiber-reinforced roofing sheets, etc. [121].

Asbestos fiber presently used in cement matrix for the production of asbestos sheets leads to serious health hazards. AMPRI, Bhopal has developed a technology to effectively utilize fly ash along with organic fibers for the production of corrugated roofing sheets.

Sisal Fiber-Reinforced–Fly Ash Cement Roofing Sheets

This product is an alternative to the carcinogenic asbestos cement sheets. The strength of sisal/cement sheet is comparable with asbestos cement sheets. The microstructure of sisal fiber within a cement matrix is shown in Fig. 22.9, showing good improved interfacial bonding. Sheets can be made manually or mechanically. It thus has great potential for use in rural areas. These products can be used in roofing, partitions, etc.

The salient features of this material are:

- It is a good substitute for asbestos cement roofing sheets
- Only renewable natural resources are used
- It is eco-friendly
- It can be repaired
- It has no health hazards
- It can generate employment in the rural areas
- It is cost-effective

Fig. 22.8 Sisal fiber cement roofing sheet

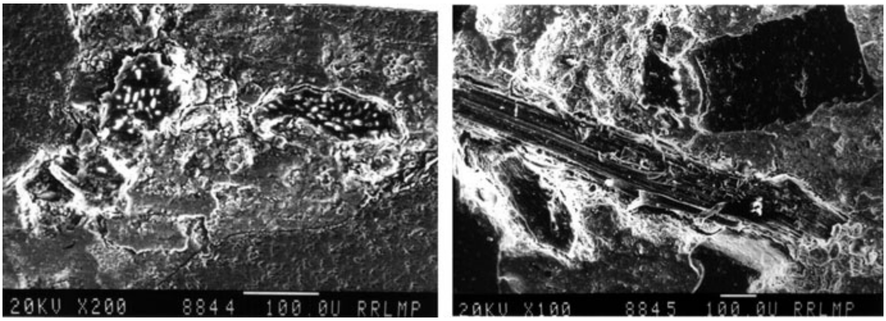


Fig. 22.9 Cross section of Sisal fiber with cement matrix

Wood Substitute Products

Natural fiber (jute fabric) and industrial wastes are used along with polymer to make composite wood substitute products. In this process, processed fabric of jute fiber and industrial wastes such as fly ash/red mud/marble slurry dust with polymer were synthesized in molds of required length and width. The composite laminates were fabricated with requisite pressure and cured at room temperature. Various products such as full size door shutters and panels can be fabricated and designed according to requirement. The industrial waste-based polymer composite products are comparable to natural wood and thus could be used as a wood substitute for doors, windows, ceilings, flooring, partitions, and furniture, etc. The products are cost-effective and no further maintenance is required. This is an environment friendly product with fruitful utilization of fly ash/red mud/marble slurry dust (Table 22.14).

The salient features of the products are:

- Stronger than wood
- Weather resistant and durable
- Corrosion resistant
- Termite fungus, rot and rodent resistant
- Fire retardant, self-extinguishing
- Cost effective and maintenance free

Table 22.14 Properties of the developed composites

S. No.	Properties	Red mud jute fiber polymer composite	Red mud sisal fiber polymer composite	Fly ash jute fiber polymer composite	Fly ash sisal fiber polymer composite
1.	Density (gm/cm^3)	1.72–1.76	1.60–1.64	1.64–1.68	1.60–1.68
2.	Moisture content (%)	0.20–0.38	0.48–0.56	0.42–0.48	0.40–0.50
3.	Modulus of rupture (N/mm^2)	85.00–95.00	78.00–88.00	80.00–92.00	83.00–90.00
4.	Tensile strength (N/mm^2)	22.00–24.00	18.00–23.00	20.00–22.00	20.00–23.00
5.	Compressive strength perpendicular to surface (N/mm^2)	78.48–101.00	70.00–95.00	75.00–95.00	78.00–98.00
6.	Compressive strength parallel to surface, (N/mm^2)	44.00–51.00	42.00–50.00	42.50–51.50	41.00–48.00
7.	Water absorption				
	2 h (%)	0.15–0.40	0.20–0.35	0.18–0.38	0.17–0.32
	24 h (%)	1.10–1.50	1.15–1.40	1.15–1.30	1.25–1.35
8.	Swelling in water				
	Length (%)	0.00–0.36	0.00–0.48	0.00–0.52	0.00–0.80
	Width (%)	0.00–0.47	0.00–0.62	0.00–0.70	0.00–0.95
	Thickness (%)	0.00–1.38	0.00–1.30	0.00–1.78	0.00–1.78
9.	Fire residency's (duration of self extinguishing)	15	20	18	22

Source: Saxena et al. [121]

Table 22.15 Building materials/components

S. No	Building materials	Composites	Plant fiber used	Institute(s)
1.	Furniture, doors, panels	R-Wood	Jute	AMPRI, Bhopal
2.	Doors and panels	Bamboo mat board (BMB) Bamboo mat veneer composites (BMVC)	Bamboo	AMPRI, Bhopal IPIRTI, Bangalore BMTPC, New Delhi
3.	Panels	Sandwich composites	Sisal and jute	AMPRI, Bhopal CBRI, Roorkee
4.	Roofs	Corrugated roofing sheets	Sisal Coir/wood wool Bamboo	AMPRI, Bhopal CBRI, Roorkee IPIRTI, Bangalore
5.	Doors	Jute pultruded door frames, medium density composites	Jute coir	CBRI, Roorkee
6.	Wood substitute	Poly coir	Coir fiber	NIIST, Tiruvananthapuram
7.	Partitioning, false ceiling, surface paneling, roofing, furniture, cupboards, wardrobes	Natural fiber reinforced boards	Jute and coir	Natural Fibertech, Bangalore NIRJAFT, Kolkata

Source: http://www.expresstextile.com, 2005

- Incorporation of jute fabric with other raw materials such as in red mud/fly ash/marble slurry to polyester increased the tensile strength, modulus of rupture, and resistance to abrasion (Table 22.14).
- Suitable combination of jute fabric, polyester, and industrial wastes can be used to get the desired properties of the laminates.
- The developed composites have the potential to be used in a variety of engineering applications, for instance, as wood substitutes, which will help in reduction of deforestation and environmental pollution.

Addition of jute fabric improved reinforcement in the composites leading to improvement in the latter's mechanical properties. Incorporation of red mud in these composites increased the density, modulus of rupture, and resistance to abrasion. However, the impact strength is reduced. This property can be improved to some extent by the addition of sisal fibers. Reinforcement of red mud imparts high abrasion resistance, which makes it suitable for flooring tiles. Various building components manufactured by using some plant fibers are shown in Table 22.15.

Sisal Fiber Composites

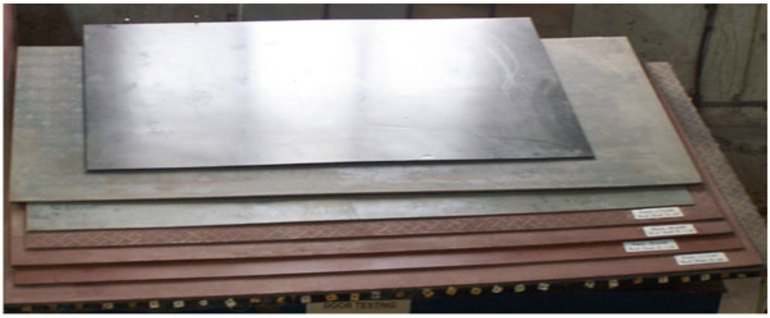
In order to effectively exploit the potential of sisal fiber, jute fibre for various engineering applications, the building materials development group at Advanced Materials and Processes Research Institute (AMPRI) Bhopal has set up facilities for the advanced and user-friendly inputs on sisal fiber-based technologies for sustainable rural employment, income generation, followed by training for entrepreneurs and rural Indians. In addition, deliverables drive the development of sustainable processes, with a comprehensive package of green technologies for sisal fiber-reinforced composites for use in a wide spectrum of applications, as shown in Fig. 22.10.

22.6.2 *Automotive Applications of Sisal Fiber*

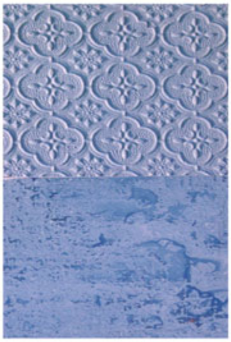
Plant fibers show significant contribution in automobile applications due to characteristics such as high stiffness with light weight per unit area, easy to recycle, 30–40% lighter than glass fiber; reduced fuel consumption, low cost, no wear of tooling, no health hazard, good thermal and acoustic insulating properties etc. Actual industrial demand for natural fibers has increased only over the past few years. In 2005, the first time natural fibers (without wood and cotton) were used in automotive composites [131]. Natural fiber composite materials are being used for making many components in the automotive sector [132].

Sisal and jute fibers have been used in the German automotive industry for years [121]. Mercedes first used jute-based door panels in its E-Class vehicles in 1996. Then in September 2000, Daimler Chrysler began using natural fibers for their vehicle production based in East London, South Africa. The company was able to implement technology transfer from their German plants to South Africa for the entire process chain. This included farming of sisal, processing of fibers, manufacturing of components and the release to the Mercedes Benz Plant of Daimler Chrysler South Africa [26]. In recent years, there has been increasing interest in the replacement of glass fibers in reinforced plastic composites by natural plant fibers such as flax, hemp, and sisal parts [53]. Like glass, the natural fibers combine readily with a thermoplastic or thermosetting matrix to produce commodity goods [133]. The automotive industry requires composite materials to meet performance criteria as determined in a wide range of tests. Typical market specification includes ultimate breaking force and elongation, flexural properties, impact strength, fogging characteristics, flammability, acoustic absorption, suitability for processing: temperature and dwell time, odor, water absorption, dimensional stability, and crash behavior [26].

Plant fibers are currently only used in the interior of passenger cars and truck cabins. Besides their use in trim parts such as door panels or cabin linings, plant fibers are used extensively for thermo-acoustic insulation. Such insulating materials, mainly based on cotton fibers recycled from textiles, have relatively high fiber content of more than 80% by weight. Trim parts in Brazilian trucks, made of a mixture of jute, coffee bag wastes, and polypropylene bags show that recycling



Panels for partitions



Tiles

Doors

Fig. 22.10 Natural fiber based wood substitute products

sometimes can lead to advanced applications. Another well-established field of application is the use of coconut fibers bonded with natural latex for seat cushions. For this application the ability of plant fibers to absorb large amounts of humidity leads to an increased comfort that cannot be reached with synthetic materials. Aside from this kind of developments, fundamentally new applications have not been realized in recent years.

Table 22.16 Various automotive parts made with plant fiber composites

S. No.	Automobile	Parts	Plant fiber used
1.	Brazilian Trucks	Trim parts seat cushions	Jute coir
2.	Mercedes Benz (E-Class)	Door panels	Sisal/flax
3.	Mercedes Benz (C-Class)	Rear panel shelf	Sisal, cotton
4.	Mercedes Benz (S-Class)	Inner door panels	Hemp
5.	Chevrolet Impala	Trim panels	Flax
6.	Daimler Chrysler (M-B Travego Coach)	Engine and transmission cover 95% recyclable vehicles	Sisal, flax, coir, hemp, cotton
7.	General Motors (Opel Astra/Vectra)	Inner door panels, Seatbacks	Hemp, Kenaf, Flax
8.	Toyota	Package shelves	Kenaf

Sources: Rai and Jha [134], http://www.osec.ch, http://www.acmainfo.com, http://www.siamindia.com, Sharma [135]

Natural fiber composites with thermoplastic and thermoset matrices have been embraced by European car manufacturers and suppliers for door panels, seat backs, headliners, package trays, dashboards, and many interior parts (Table 22.16). Natural fibers such as kenaf, hemp, flax, jute, and sisal offer such benefits as reduction in weight, cost and CO_2, less dependence on foreign oil sources and recyclability. Glass fiber reinforced plastics have proven to meet the structural and durability demands of automobile interior and exterior parts. However, it exhibits shortcomings such as its relatively high fiber density (40% higher than natural fibers), difficulty to machine, poor recycling property, and potential health hazard. An ecological evolution of natural fiber mat as compared to glass fiber mat offers another prospective use of natural fiber reinforcement. Flax, sisal, and hemp are processed into door cladding, seatback linings, floor panels, and various other automotive parts [53].

Various automotive parts made of natural fiber composites are shown in Table 22.16. The use of plant fiber (sisal/flax/hemp etc.) based automobile parts such as trim parts, various panels, shelves, and brake shoes are attracting automobile industries worldwide because of its weight reduction, energy and cost saving. Conservative estimates indicate that about 6,000 TPA plant fiber-based composite parts can find their way into passenger cars and multi-utility vehicles [17].

Sisal is used in door cladding, seatback linings, and for packaged shelves (the space behind the rear seats of sedans). The BMW group incorporates a considerable amount of renewable raw materials in to its vehicles. Each BMW 7 series car boats 24 kg of renewable raw materials, with flax and sisal in the interior door lining panels [136].

Prospects for the Use of Sisal Fiber in Automotive Industry

Door panels; cabin linings; brake liners; thermo-acoustic insulation; trim parts: seat cushions and backs; headliners; package trays; dash boards; trunk liners. The possible stakeholders for the utility of sisal fiber in automotive components industry are: Mercedes Benz, Freightliner, Daimler Chrysler, Chevrolet, and General Motors, Mahindra & Mahindra, Tata Motors and Hero Honda etc.

The cost benefit analysis, techno-commercial feasibility, and the challenges for sisal fiber exploitation for various engineering applications are as follows:

- Sisal is a xerophyte, grows in wastelands. Conserves soil and earns carbon credits
- Assured sustainable fiber production: 2.5 ton/ha for 6–8 years
- Surface treatments enable sisal fibers to be used as reinforcement in a polymer matrix
- Advantageous over mineral and other conventional natural fibers

22.6.3 Electrical Application of Sisal Fiber

In order to utilize sisal fiber for electrical applications, several researchers have studied different electrical properties of sisal fiber at different temperatures and frequencies. The work carried out by Xin et al. [138] showed that an increase in frequency decreases the dielectric constant 'ε' whereas an increase in temperature increases at all frequencies. Increasing the plant age shifts the dissipation factor (tan δ) peak to higher temperature.

Further, these phenomena were explained on the basis of structural charges. Water absorbed by sisal fibers has OH^- anions which act as dipoles. Other than OH^- anions, there are several impurities and ions on the fibers. These dipoles and ions contribute to the ε' and tan δ behaviors of sisal fiber. At low frequencies, high ε' and tan δ values in sisal fiber are caused by the dipolar contribution of absorbed water molecules. ε' Values at intermediate frequencies are the result of contributions from space charge polarization. At high frequencies, the contribution of polarization of absorbed water molecules and space charge decreases and electronic and atomic polarization becomes operative. Increase in temperature affects the mobility of ions and consequently changes the ionic contributions [139, 140].

The electrical properties of sisal fiber reinforced LDPE have been studied with respect to the effects of frequency, fiber content, and fiber length. The dielectric constant increases steadily with increasing fiber content for all frequencies in the range 1–10^7 Hz. It is also noted that dielectric constant decreases with an increase in fiber length and frequency. Maximum dielectric constant values are obtained at low frequencies. Sisal/LDPE composites of 1 mm fiber length and 30% fiber content have the highest values of dielectric constants at all frequencies. The values of volume receptivity decrease with increase of frequency and fiber content i.e., the electric conductivity of composites are greater than neat LDPE. When compared to glass/LDPE composites, the same trend in electrical properties is observed, but the charges of dielectric constants of the latter composites with frequency and fiber content are smaller as a result of their lower interfacial polarization. The dielectric constant, dielectric loss factor, and electrical conductivity of 25% sisal LDPE can be increased considerably by adding 5% carbon black. The composites can be used in antistatic applications to dissipate static charges [56, 57].

22.6.4 Application of Sisal Fiber in Railways

Composite materials offer some significant advantages to metals in many structural applications in railways to the effect that they are lightweight, cost-effective, corrosion resistant, energy saving, wear resistance and fire retardant. In railways, the gear case, main doors, luggage racks, floor/roof panels, berths, chair backings, interior panels and partitions, interior furnishing and seating, modular toilets, and lightweight coaches are made from different natural fiber composites and their combinations. Weight savings of up to 50% for structural and 75% for nonstructural applications bring associated benefits of high speed, reduced power consumption, lower inertia, less track wear, and the ability to carry greater pay-loads. Natural hard fibers such as coir, jute, etc. impregnated with phenolic resins are used for manufacturing of composite boards. Eighty percent of the materials used in the composite are natural fibers [121]. In the railways, sisal fiber has major role for potential application in many areas. Indian Railways have initiated action for introducing composites in the coaches. In facts, for a mass transit system, lightweight coaches are important for achieving higher speed. The present use of GRP products due to its corrosion resistance and workability would also be substituted with natural fiber composites. Already, the natural 1.6-mm thick fiber thermoset composites are being used by the railways for roof ceiling, flooring, and is targeted to substitute timber and plywood usage in the coach [155]. Natural fiber-based composite materials in India have great scope in the railways where the resulting performance improvements would be significant in terms of weight savings, high-speed, reduced power consumption, lower inertia, less track wear, etc. It is estimated that about 350 TPA fiber composites is required in the Indian railways for manufacturing of doors, luggage racks, panels, partitions, seating, etc. [17, 141].

22.6.5 Application of Sisal Fiber in Geotextiles

Geotextiles have been used for many years in roadway construction and soil stabilization to avoid soil erosion. Geotextiles were made of natural fibers, fabrics or vegetation mixed with soil even in the past. In recent days, geotextiles have been in use for modern road construction. Geotextiles are the subfamily in the large family of “Geosynthetics”; other subfamilies include geogrids, geonets, geomembranes, geosynthetic clay liners (GCL), geopipes, and geocomposites. Geotextiles are woven and nonwoven fabrics. A geotextile can be made either using synthetic or natural fibers. It is designed in such a way as to be permeable to filtrate fluids and control migration of soil. Geotextiles can be woven, knitted, or nonwoven and can be fabricated suitable for different applications. The nonwoven geotextile is an arrangement of fibers either oriented or randomly patterned. These geotextiles support water flow in addition to stabilization of soil. There are many other uses of geotextiles such as roads, aggregate drains, pavement overlays, and erosion control. Recent development in this area is the use of natural geotextiles, which include fabric formed using coir, sisal, and the natural fiber from the husk of coconuts. These geotextiles have exceptional strength due to the high content of cellulose lignin polymer in them. Besides, they are naturally degradable, which may be attractive in certain applications such as natural stream bank restoration. Other natural fiber geotextiles include jute, mixed coir jute, and mixed sisal jute. The market potential of geotextiles for roads, paved road networks, and railways applications in India is estimated to be 272,500 tons, for which sisal textile can also be used [130, 142, 143, 150].

22.6.6 Defense Applications of Sisal Fiber

There are six main fields of applications for military use that might be of immediate interest in the use of biofiber materials. These are uniforms and other textile applications, personal safety equipment, transportation vehicles, field housing and other construction, packaging, weapon components, and utility tools. Defense applications include protective clothing and systems integration in the textile itself. In addition to the different composite materials, a steel composite hybrid system is also made. With the current generation of biocomposites for military transport vehicles, most applications would be interior, such as various panels, dashboards, and also textiles. The basic advantages would be the same as for the civilian industry. Cellulose fiber-based composites would make excellent packaging materials due to their light weight and biodegradability.

22.6.7 Application of Sisal Fiber in Packaging Industry

Sisal fiber has very important contribution to meet the future challenges of environmental sustainability in the packaging market. This has further mass scope when it combined with bio-based polymers in developing composite materials to use as packaging materials in the future. The packaging materials for bags, boxes, crates, containers, which are now made of wood can be replaced by cost-effective sisal fiber reinforced composites [17]. The estimated demand for the package materials works out to 93 lakh tons.

22.6.8 Other Applications of Sisal Fiber

AMPRI, Bhopal is involved in R&D activities on sisal fiber extraction, processing, and product design. It has developed a versatile machine (Raspador) for the mechanical extraction of sisal fiber. The laboratory has been imparting training to people in rural areas, especially women, to make handicrafts of sisal fiber. AMPRI has also developed vermicomposting technology using sisal leaf residue to produce eco-friendly manure. Based on its expertise, the laboratory has developed sisal fiber-reinforced corrugated roofing sheets and sisal fiber–polymer composites, which are alternate building materials superior in quality, eco-friendly, noncarcinogenic, and cost-effective. Basic research and design need to be carried out for the development of crimp to make yarn and various surface treatments and processes to overcome its hydrophilic nature, improving the interfacial bonding and mechanical properties of the fiber. The "Building Materials Characterization and Testing Center" and "Technology Enabling Center" for natural fiber composites are the additional expertise and facilities available. Sisal fiber research and its allied activities such as cultivation, fiber extraction, processing and making value added products are proven sources of employment opportunity and income generation. The present experience indicates that trained artisans and women are able to generate a sustained income through the sisal-related activities. The engineering applications of sisal fiber such as buildings, automotives, railways etc. are prospective areas that can generate employment. The ease with which fiber can be produced on wastelands in a wide range of agro-climates, the sustained fiber yield for a considerably long duration, and the versatility of the fiber as a potential input material for various applications make it a viable option for employment generation and rural development.

1. *Use in Vermicomposting*: After extraction of the fiber from the leaves about 95% green pulp is obtained in the form of residue. The sisal green pulp is a source of organic matter and this residue will be utilized for manufacturing eco-friendly and valuable vermicompost. This aspect covers the comprehensive utilization of sisal. In vermicomposting, degradation of bio-residues is done with the help of earthworms (Eisenia Foesia). This ecofriendly organic manure is rich in nitrogen, phosphorous, potassium, and organic matter [16].
2. *Use in Biodegradable Polymers*: Development of biodegradable materials as an alternative to synthetic materials such as glass fiber-reinforced plastics and other synthetic plastics is the challenge for the present and future generations in the context of global climate change. Moreover, there are various problems associated with synthetic polymer composites due to the inherent problem of life cycle assessment and waste management at the end of its service life. At this juncture, biodegradable materials offer significant advantages provided they are techno-economically viable. Worldwide, considerable work is being done by several researchers for the development of biodegradable polymers leading to manufacturing of biodegradable polymer composites for various engineering applications. The problem related to finding available landfill areas for the final disposal of nonrecyclable polymers has also given rise to the development of biodegradable polymers and blends able to fulfill the new environmental requirements regarding the effective management of waste. Biodegradable polymers have been combined with natural fibers to produce environmentally sound

biocomposites. The addition of short sisal fibers is found to be cost beneficial by decreasing the polymer volume fraction with additional improvement in properties, such as thermal stability, creep behavior, and mechanical properties [18, 144].

3. *Biogas from Sisal Fiber Waste*: In most developing countries, agro-industrial residues are available in abundance. Sisal fiber extraction by-products have been evaluated for animal food production and sisal waste is a good material for biogas production [145]. These wastes have great potential in catering to the energy demand, especially in the small-scale local energy sector. Bio-methane from sisal fiber wastes, a waste product of the sisal industry, is of great importance as a renewable energy carrier that could be used for cooking and power generation [8]. Sisal waste has proved a good feed for anaerobic reactors to produce biogas and this biogas could be used for the generation of electricity [146]. Pilot scale demonstrations show that it is a valuable feedstock for biogas plants to cater to local and rural energy requirements. One ton of sisal pulp can generate 54.3 m^3 of biogas by the methanogenesis [146]. Sisal leaves are known to contain wax (0.38%) and hecogenin (0.10%). These expected spin offs are in the form of secondary/allied activities which are labor intensive and have applications in rural and small-scale industrial sectors. The stored biogas made by sisal waste can be used to run two 150 Kw electricity generators for a rated total electricity output of 300 Kw; biogas can also be used in cooking [147]. One of the latest study reports for the first time a two-stage fungi pretreatment for enhanced biogas production from sisal leaf decortication residues. The increase in methane yield is attributed to improved biodegradability of sisal residues after pretreatment. However, there is a great potential of methane generation from biological pretreatment using fungi; further research is required to establish the mechanism of such improvements [7].

22.7 Conclusions and Future Prospects

The results of recent research revealed that plant-based fibers can be effectively used as a reinforcement in polymer matrix composites, replacing synthetic fibers to some extent.

Sisal fiber has relatively high stiffness and low cost, but the disadvantages are high moisture sensitivity and variation in fiber properties. Interest in using sisal fiber in composites has increased in recent years because such composites are lightweight, nonabrasive, nontoxic, and biodegradable. The physical and chemical methods of treating sisal fiber composites improved their mechanical properties because of increased fiber matrix adhesion. Sisal fiber is a potential reinforcement material in polymers, rubber, and in gypsum and cement matrices. This has resulted in innovative technological applications beyond its traditional uses in ropes, carpets, mats, handicrafts, etc. The use of sisal fiber as a renewable raw material in the plastics industry shows potential uses in the manufacture of different composites. Use of sisal waste has also shown to conserve resources, produce manure and other valuable byproducts (wax and hecogenin) and generate energy (biogas and electricity).

Recently sisal fiber has been autoclaved to get pulp for spinning into the yarn. Further research may focus on the utilization of better or mechanized yarn making/ spinning technology to achieve better yarn consistency and higher productivity leading to production of high quality sisal fabric. Also, serious efforts may be initiated for sisal yarn and fabric making as it has not yet been commercially exploited as a reinforcement in composites. Because of the low density and high specific properties of sisal fibers, composites based on these fibers have good applications in the electrical, automotive, railways, buildings materials, boats, geotextiles, defense, and packaging industries. Moreover, reduced equipment abrasion and subsequent reduction of cost will make these composites more attractive.

The present scenario indicates that the use of plant fiber (sisal/flax/hemp etc)-based automobile parts such as trim parts, various panels, seat backs, shelves, brake shoes, etc., are picking up momentum worldwide. Conservative estimates indicate that about 6,000 TPA plant fiber-based composite parts can find their way into passenger cars and multiutility vehicles. Railways are also a potential application industry where it is estimated that about 350 TPA fiber composites will be required in India for manufacture of doors, luggage racks, panels, partitions, seating, etc.

There is a scarcity of sisal fiber supply and a sustainable supply chain needs to be established. For the sustained supply of sisal fiber to make sisal chopped strand mats, sisal fabrics, and composites for user industries, fiber production has to be increased. To achieve this, a larger area has to be brought under sisal cultivation. Mechanical extraction using raspador/decorticator consumes energy; besides, the fiber gets damaged resulting in poor mechanical properties. Therefore, to make the fiber cost-effective and technically sound for engineering applications, further modification in the existing decorticator needs to be made. Sisal textile composites are showing better performance as compared to chopped strand mat composites. The problem faced in making the fabric from sisal fiber is crimping. This is hindering the process of yarn and fabric making. The existing processes for generation of crimp in sisal fiber/fabric looms are only of academic interest, lab scale, and not commercially viable. Hence, some alternative path needs to be evolved following suitable methodologies such as separation of cellulose microfibrils following a microbiological approach for spinning into the yarn. Future research may focus on utilization of better or mechanized spinning technology to get better yarn evenness and higher productivity.

A study on hybrid composites of sisal fiber with other natural fibers or synthetic fiber is needed to achieve optimum benefit for broader applications. Sisal fiber/ matrix interface and relationship between interface and bulk composites need to be studied in detail for a better understanding leading to the development of a unique process for better bonding between fiber and matrix and compatibility with a wider range of other materials/components. Further R&D, new initiatives, and innovation are needed to develop a unique mechanism for the manufacture of environmental friendly and cost-effective processing methods for the composites, and to understand the relationship between processing methods and mechanical properties of the composites and recycling characteristics/options of the sisal fiber reinforced composites, gaining energy and ecological advantage. It is essential to develop/use matrix materials based on renewable/biodegradable resources such as biodegradable polymers. The engineering applications of sisal fibers are the prospective areas and the utility of the sisal fiber makes it a viable option for employment generation and rural development. Further systematic and persistent research on sisal fiber-based technologies will lead to greater scope in the use of this plant resource

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