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Review Article

Natural fibres as sustainable engineering materials: scope, challenges, and prospects

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Natural fibres are increasingly becoming popular in various geotechnical applications. Being environment-friendly renders them a more appealing choice over the polymer-based counterparts. However, the strength and deformation properties and the long service life of synthetic polymer fibres cannot be matched by natural fibres. Natural fibres and geotextiles have been found to lose strength over time while in use. Among the tropical fibres, coir has better longevity due to its high lignin content. In-field studies presented in available literature conclude that the tensile strength of coir geotextiles drops by around 80% of its actual strength within the initial year of its installation in a tropical climate, whereas the strength loss for jute geotextiles takes place at an even faster rate. Investigations on the durability enhancement of natural fibres for composites have been reported worldwide. Most of the chemicals used for surface modification are considered expensive, hazardous and unsuitable for geotechnical applications. Moreover, certain types of modifications alter the desirable properties such as drapability, flexibility and fibre strength, which are the crucial characteristics for geotextiles. A critical review of the fibre modification methods attempted to date has been presented. The effectiveness of plant-based natural components on the surface modification of natural fibres and the challenges that may arise are also reviewed. Despite the research reported in the past, it remains necessary to pursue further investigations until natural fibres/geotextiles with suitable environment-friendly treatments emerge as viable and sustainable alternatives to synthetic geosynthetics. Given their cost-effectiveness, local availability, and reduced carbon footprint, natural fibres/geotextiles with an extended useful life can serve as superior alternatives to synthetic geotextiles for long-term engineering applications.

Keywords: Biodegradation, Coir, Geotextiles, Natural fibres, Sustainable material

1 Introduction

Engineers are often bound to adopt an environment-friendly approach towards solving numerous engineering problems. Based on the increased environmental and energy awareness, expensive synthetic fibres are gradually being replaced by renewable plant fibres in such applications. Natural fibres are complex heterogeneous polymers made up of lignin, cellulose, hemicelluloses, pectin and wax-like substances in various proportions and are commonly known as lignocellulosic fibres (LCFs). They find applications in various forms such as fibres, yarns and fabrics[1]. Renewable natural fibres have already been identified as a potential substitute for energy-intensive synthetic fibres in situations which do not require high strength and modulus.

Geotextiles form one of the largest groups of geosynthetic materials. They are permeable textiles made of synthetic or natural materials. Compared to the conventional construction practices adopted in solving engineering problems, geosynthetics-based practices are considered more sustainable[2,3]. Natural geotextiles are more environment-friendly when compared to their synthetic equivalents in terms of their carbon footprint. Natural geotextiles play a prominent role in addressing a wide range of geotechnical engineering problems safely, efficiently and economically[4]. Being flexible and drapable, these geotextiles adapt themselves to the unevenness of the ground. Flax, hemp, jute, sisal, abaca and coir are identified as the six most promising LCFs suitable for geotextile manufacturing[5]. Woven coir geotextiles with varying densities are shown in Fig. 1.

However, the hygroscopic nature of natural fibres is the main challenge in manufacturing sustainable end products. Natural fibres are reported to lose strength with age, and the degree of strength loss varies among fibres of different origin[6]. The high biodegradability of natural fibres often poses problems that limit their presence in long-term

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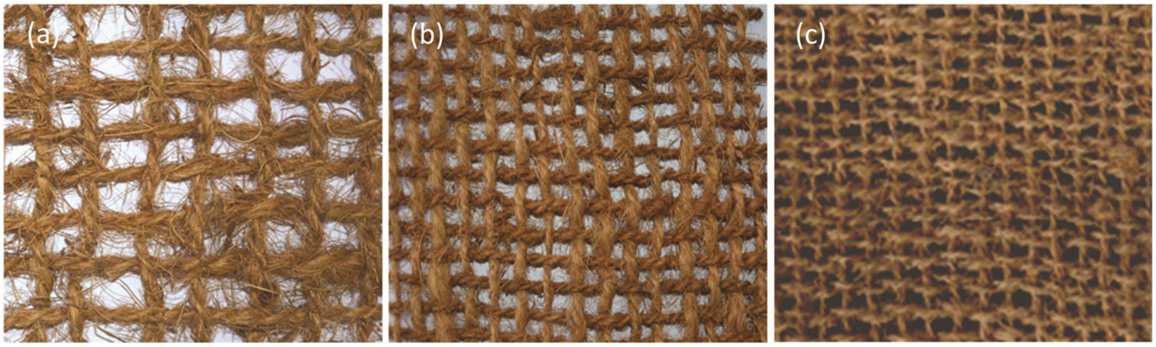

Fig. 1 — Coir geotextiles of varying densities (a) 700 g/m^2, (b) 1025 g/m^2, and (c) 1150 g/m^2

engineering applications. The degradation rates are more predominant in wet conditions that prevail in tropical regions[7,8]. Therefore, it becomes imperative to subject these fibres to modification procedures before utilising them in engineering applications[9]. Such processes focus on one or more of the following: surface preparation, cleaning, alteration of surface properties, enhancement of the mechanical properties and reduction of the moisture absorption rate[10]. This paper reviews the various aspects of natural fibres that render them suitable for sustainable engineering applications. The challenges involved in these processes and the recent approaches to address them - placing special emphasis on coir fibres/geotextiles - have been critically analysed.

2 Structure and Composition of LCFs

The chemistry and structure of natural fibres are the key factors that decide their characteristics, efficiency, and end use. Lignin, cellulose, hemicellulose, pectin and waxes form the basic components of any natural fibre. Based on the variations in proportions of these basic components, each type of fibre responds to the surrounding environment in its own unique pattern[11,12]. The cell wall in a fibre has a complex structure with a heterogeneous membrane comprised of a compound arrangement, as illustrated in Fig. 2. Lignin and cellulose form the major building blocks along with hemicellulose and pectin. The fibre gathers thickness as it grows. The structural strength of the fibre is contributed by cellulose molecules, which exist as microfibrils in a helically wound configuration in the middle of the fibre. The angle that the microfibrils make with the fibre axis is a major strength-determining factor, in addition to the fibre thickness[13].

Lignin is a complex hydrocarbon polymer that gives strength, rigidity, hardness, mechanical support, reinforcement and biological resistance to the fibre. The systematic arrangement of cellulose molecules determines the cell wall framework of a fibre. Crystallinity of cellulose regulates the reinforcing ability of the fibre. Cellulose is a hygroscopic material insoluble in water and dilute acid solutions at low temperatures. The hydroxyl groups in the cellulose contribute flexibility to the fibres. Hemicellulose possesses an affinity towards water. Pectin binds the neighbouring cells, including cellulose and hemicellulose, together. Wax and other fatty substances form protective tissue and reduce water loss through the cell wall. In a natural fibre, cellulose is responsible for the cell wall structure, hemicelluloses for thermal, biological and moisture degradation and lignin for mechanical

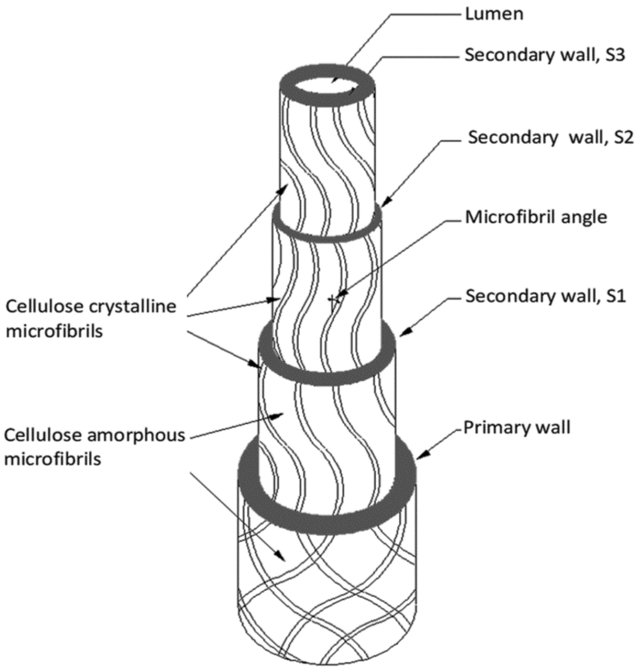

Fig. 2 — Cross-section of a natural fibre[13]

reinforcement[14]. Thus, the comprehensive identity of a fibre is the net contribution by the various components that constitute the fibre.

Based on the chemical composition, the various LCFs display wide variations in their physical and structural properties. Jute fibres are long and soft, with high initial tensile strength. Coir has less tensile strength, but exhibits high durability and very slow and progressive loss of tensile strength with time[7]. Hemp fibres exhibit a high degree of drapability and endurance in harsh environments. Sisal fibres possess high tensile strength, approximately thrice that of coir fibres. Low-density fibres such as hemp, flax and kenaf are largely harvested and are utilised in composite manufacture[1]. Fineness, extensibility and non-allergic properties make cotton an ideal raw material for textile production[5].

Coir has the widest engineering applications out of the various natural fibres due to its highest tensile toughness[15]. Most natural fibres, such as jute and sisal, are grown for fibre production, whereas coir is a byproduct obtained in coconut production[16]. While considering the net cost of production of similar natural fibres, the utilisation of coir can be regarded as highly economical. The yield of coir fibre greatly depends on the retting process, season of retting and the method of extraction[17]. The share of natural geotextiles accounts for merely 5 % in the market compared to their synthetic counterparts. Remarkable properties such as flexibility, drapability, frictional resistance and high tearing strength under moist conditions make coir geotextiles a superior choice for erosion control as well as ground/subgrade improvement applications over the other natural geotextiles[18-20]. Tensile strength of coir geotextiles primarily depends on their chemical composition and the microfibril angle. Coir shows great resemblance to wood fibres with regard to physical properties and chemical composition. There is an abundance of resources and immense research potential in applying modern science and technology to mass-produce and enhance coir and coir products.

3 Fibre Composition and Fibre Properties

The structural and mechanical behaviour of natural fibres of identical type, but diverse origin, cannot always be the same. Degradation depends on various factors such as the chemical composition of LCFs, the source of fibres and the mode of extraction. Each component in a fibre cell behaves independently towards chemical reagents[21]. Lignin is highly hydrophobic and provides brittleness to the fibre. LCFs such as coir with high lignin content suffer less degradation due to acids. An alkaline medium at an elevated temperature is reported to make the lignin soluble. Due to the presence of closely packed hydroxyl molecules, crystalline cellulose is more hydrophobic and shows high resistance to degradation due to hydrolysis and chemical actions[22]. However, it easily degrades into soluble sugar in an acidic environment. Amorphous cellulose can resist degradation due to microbes, oxidising agents and alkalinity. Hemicelluloses are easily degraded in acidic and alkaline media due to their branched and amorphous nature. Higher concentration of hemicelluloses in an LCF results in reduced tensile strength. Pectin exists in two forms: water-soluble and water-insoluble. Waxes are the esters of alcohols and are neutral towards chemical and hydrolysis reactions. Wax accumulation on fibres restricts the entry of microorganisms. Removal of pectins and waxes disintegrates fibre bundles into rough-textured elementary fibres[23].

4 Geotechnical Engineering Applications of Natural Fibres/Geotextiles

The primary functions that geosynthetics perform include reinforcement, filtration, separation and drainage[24]. Geosynthetics are manufactured to fulfil the specific properties that each primary function demands. For the reinforcement applications, tensile strength is a primary property, while durability is a secondary property dependent on the life term required. Durability studies of geotextiles are to be carried out over a long duration with special emphasis on possible physical, chemical and biological influences.

Geotextiles find immense applications in enhancing soil properties. Soils with very high compressibility and relatively low shear strength can be modified to suit several applications by integrating coir geotextiles[25]. Stabilisation of weak slopes from erosion has been widely carried out using coir and jute geotextiles in tropical regions [26,27]. Structural modification of geotextiles has been reported to successfully overcome the geographical challenges in such cases[28]. Natural geotextiles assist in regulating the drainage along embankments in the form of blanket drains or vertical drains[29,30]. Jute geotextiles coated using bitumen are reported to perform as a successful fabric form as well as a secondary liner[31]. The suitability of utilisation of natural fibres and geotextiles for heavy metal containment[32] has also been reported.

Most of the natural fibres possess inherent tensile strength, and this property has been utilised to reinforce weak soils in many parts of the world[33,34]. Natural geotextiles find wide applications in providing support to temporary structures. They serve as effective reinforcement for temporary clay structures in wetland conditions[35]. The development of cracks in soil due to shrinkage can be restricted to a great extent by making use of the tensile properties of the natural fibres. Bamboo, jute and coir are employed in such applications based on the availability[36]. Limited-life geotextiles derived from short-life fibres such as banana and kenaf are increasingly being used to enhance soil properties[37,38].

The core of creating geosynthetics from natural fibres lies in functional design, wherein functions and necessary characteristics are identified to address a specific problem and are manufactured accordingly. Though natural fibres possess numerous characteristics favourable for enhancing soil properties, a well-engineered design is essential to bring them on par with synthetic fibres[39]. The end use of geotextiles/yarns demands the ideal fibre orientation design. In applications where the geotextiles partially contribute to load bearing, the weak joints must be restricted to a minimum. This is highly challenging as almost all the natural fibres possess only a discrete length. To gain the maximum efficiency of fibres, a high level of quality control is to be ensured to convert the fibres to continuous products in the form of yarns/ textiles to suit load-bearing applications[40].

5 Effect of Environmental Factors on Degradation of LCFs

Lignocellulose is a complex substrate which follows a complex degradation pathway in a biologically active environment. Environmental conditions, as well as the degradation capacity of microorganisms play an equal role in lignocellulosic degradation[21]. The degradation of natural fibres is greatly influenced by the environment associated with them during their storage and application.

Natural fibres such as coir and jute in woven and non-woven, i.e., needle-punched felts backed with polymeric nets, are extensively used to manufacture geotextiles for geotechnical engineering applications. Based on the soil conditions, geotextiles may be placed in diverse conditions of pH, salinity, moisture, weather, temperature variations, UV radiation and microbial association. The type of water that the geotextile associates with may vary with respect to the geographic location and other conditions. Thus, it is well understood that the degradation of natural fibres can be a highly complex and conflicting process[41]. Although it is recognised that high lignin content in coir helps to retain strength properties and limit biodegradation much better than its other counterparts, organised studies reported in this discipline are only a few.

Reports of previous studies state that the degradation of various LCFs is the highest under alkaline conditions, followed by acidic conditions[42]. An alkaline condition is capable of removing the oily coating and cementing materials from the fibre's surface. This alters the packing of molecular chains, thereby increasing the moisture absorption properties[43]. Alkalisation can remove hemicelluloses and lignin from fibres under optimum conditions of alkali concentration and temperature[44]. Crystalline cellulose undergoes degradation under acidic conditions. Neutral pH and saline conditions are reported to have less influence on the strength loss in certain LCFs, such as coir, due to the high lignin content[7]. High salinity in the substrate and alternate wetting and drying conditions probably fail to provide a suitable microenvironment for microbial growth.

Biological degradation of natural fibres mainly arises from the association of natural fibres with moisture. All the LCFs contain free hydroxyl and other oxygen-containing groups. Natural fibres have a porous structure and display an intrinsic affinity towards water owing to the hydrophilic groups associated with the fibre structure. Coir and jute have rough and uneven surfaces, with numerous micropores within the range 3–5 μm[45,46]. Biodegradation of natural geotextiles mostly happens due to microbial interactions, and this must be clearly addressed in engineering applications. Short-term applications, such as erosion control, mandate a moderate rate of degradation for biomeshes. However, long-term applications which include soil reinforcement, filtration and coastal protection in association with highly moist, alkaline or rich organic soils demand a slow rate of geotextile degradation in order to achieve their intended function[39].

Microbial attack initiates from the weak cell wall regions developed due to swelling under moist conditions. Numerous species of aerobic/anaerobic bacteria and fungi can degrade lignin and cellulose in the fibres through distinct mechanisms. Enzyme systems of these microorganisms convert the carbohydrate components within the fibres to digestible fractions[47]. White rot fungi secrete lignocellulose-degrading enzymes and are the primary decomposers of lignocellulosic components, whereas Actinomycetes and bacteria play the role of secondary foragers, at a very slow rate[48]. Fungal action is reported to be more predominant in moist conditions, at relative humidity above 65 %. This is much higher for bacterial activities, i.e. above 95 %. Lignin serves as the carbon source for the white-rot fungi to break down the obstacles to cellulose utilisation. The association of lignocellulosic fibres and bacteria/fungi leads to degradation pathways initiated by enzymes. This includes simultaneous hydrolysis, oxidation, and reduction[49]. Material degradation rate is determined by the ambient conditions which favour microbial growth.

Various species of microorganisms capable of utilising lignocellulosic materials have been identified through experiments. A mixed spore suspension of five fungal species, namely, *Chaetomium indicum, Aspergillus fumigatus, Penicillium rubrum, Curvularia lunata* and *Penicillium wortmanni*, is recommended as per IS 1623[50] for testing microbial degradation of jute geotextiles. Degradation of coir waste using *Phanerocheate chrysosporium* and *Rhizopus stolonifer* was also reported. Microorganisms capable of degrading specific cell components demand specific conditions, which can be a combination of various factors such as pH, temperature, moisture, humidity and presence of certain chemicals[51].

The degradation mechanism of natural fibres by macroorganisms such as silverfish and termites is entirely different from that of microbial degradation[52]. Termites of the *Rhinotermitidae* family survive in areas mostly devoid of sunlight and are capable of digesting cellulose. Lignocellulosic materials stored in moist, dark environments undergo termite degradation through biting and chewing action[53]. Termite activity is accelerated under suitable environmental conditions and the availability of food. Natural geotextiles are widely applied at shallow soil depths and are subjected to dampness during precipitation. Hence, degradation due to termite attack as well as microbial action can be anticipated in such cases. Moreover, bulk volumes of geotextiles are manufactured and stored in places prone to termite attacks. Typical degradation pathways for the degradation of natural fibres are illustrated in Fig. 3.

6 In-Field Degradation Studies on Natural Fibres and Geotextiles

When geotextiles made out of natural fibres such as jute and coir are subjected to natural soil conditions, several parameters, including the type of vegetation, climatic conditions, the type of soil, soil compressibility, soil moisture, organic content, chemical composition of the soil and gradient of the terrain, determine their durability[7,26,54]. Most available literature on natural geotextiles focuses on the applications and end uses. Life expectancy studies have been less reported, as most studies address short-term applications. Outdoor exposure followed by the observations of the reaction of the material is a commonly adopted practice in determining the life expectancy of geotextiles. Accelerated weathering tests are also conducted in the laboratory for life prediction studies[52]. Natural weathering studies depend on geographic location and environmental conditions, whereas laboratory studies depend on the accuracy of test equipment and test conditions.

In a foremost study[55] conducted in 1992, the strength properties of coir, jute and cotton geotextiles in highly fertile soil were compared. Under highly humid conditions and moderate moisture, coir exhibited superior properties with a strength retention of 20 % after one year. The fastest degradation occurred for cotton and jute, i.e., within six weeks and eight weeks, respectively. In an attempt to use indigenous materials, jute geotextiles were employed in bank protection works in the Hooghly estuary, India. Bitumen had been applied to geotextiles to

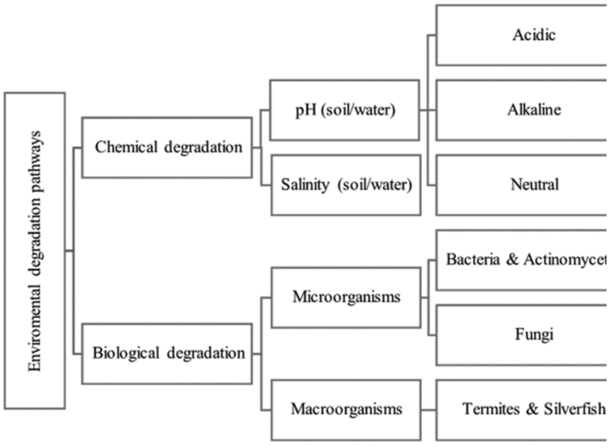

Fig. 3 — Various pathways of environmental degradation of natural fibres

arrest moisture and to make the geotextiles impervious, which ultimately contributed to rot resistance. No subsidence or disturbance of the protected stretch was reported after 1.5 years of installation[56]. In an extensive study, coir geotextiles were subjected to tropical climate conditions at two different geographical locations with different rainfall patterns[7]. In one of the burial sites where rain was intense and organic content was high, coir geotextiles buried at shallow depth lost nearly 75 % of the initial tensile strength within five months. However, the coir mattings placed on the surface lost only 44 % of their strength after seven months of installation.

The performance of coir mesh mattings of mesh opening 6 x 10.5 mm^2 and density $700g/m^2$ was monitored for one full hydrologic year for slope protection and erosion control in the tropical climate, India[26]. Anjengo type of yarn (approximate scorage of warp yarn 12 and picks per dm – 11) had been used for the study. Partially degraded coir mattings, along with the grass canopy and root system, played a major role in reducing soil erosion. Coir mattings lost 45 % of their initial tensile strength after 30 days and retained 19 % of their original tensile strength towards the end of 8 months. The effectiveness of coir geotextiles in embankment protection for watershed management in the Western Ghat Region, India, was proved experimentally[18]. In this study, geotextiles made of Vycome type of yarn (approximate scorage of warp yarn 13 and picks per dm – 8) of density 740 g/m^2, mesh size 6 x 6 mm^2 and initial tensile strength 13.8 kN/m lost 81 % of tensile strength after 9 months.

The degradation pattern of natural geotextiles varies widely along the vertical profile of soil. A field study conducted in a tropical climate[42] reveals that biological degradation of coir geotextiles (1083 g/m^2) is more profound in the top layer of soil up to a depth of 75 cm. Strength reduction up to 78 % has been reported within a burial period of 120 days. Natural degradation mechanism of coir geotextiles when exposed to fertilised and lime-treated soils has been investigated based on cellulose retention and lignin degradation. Better cellulose retention in treated fibres accounts for greater strength, while partial loss of lignin/hemicelluloses is responsible for degradation independent of exposure time. The in-field study was conducted in eastern Brazil during a one-year seasonal cycle of rain and drought. Tensile strength of coir fibres derived from geotextiles retained nearly 20 % of original strength after one year[57].

In a recently reported study, five types of natural fibres, i.e., coir, jute, abaca, sisal and pineapple fibres, were studied to assess their suitability in geotextile applications[58]. Among these, geotextiles blended with a combination of coir and sisal fibres possess high strength and less elongation. The strength properties of lignocellulosic fibres (LCFs) vary widely with respect to their structure and composition.

As per the various scientific studies carried out worldwide for more than three decades, natural fibres and geotextiles have been found to lose strength over time while in use. Although the rate of degradation does not follow identical patterns in all these studies, it can be inferred that the tensile strength of coir geotextiles lowers by nearly 80 % of its initial strength in the first year of its placement in a tropical climate. In contrast, strength loss for jute geotextiles takes place at a much faster rate. Degradation, in all the reported cases, has been accelerated by the presence of moisture, mainly due to the action of rain. Coir, a fibre with high lignin content, possesses inherent resistance to fungal moulds under humid conditions[59]. However, prolonged exposure to moisture can accelerate the rate of degradation. Dimensional changes, such as the formation of cracks, trigger microbial attack. Enzymatic activities of microorganisms become active as fibres absorb water. It is reported that moisture increases ductility and ultimate elongation of fibres, reducing the degree of crystallinity, strength, modulus and yield point. The degradation rate of these fibres in physical, chemical and biological environments largely depends on their origin, chemical composition, mode of extraction, presence of moisture and microbial association. Laboratory studies and in-field studies report that the life of natural fibres reduces with time when in use[7,42,52,54].

As natural fibres are gradually replacing synthetic fibres, it is necessary to devise novel methods to improve their strength and extend their life. Development of hybrid fibres is an upcoming area of research. In a 2019 study, a composite structured synthetic geotextile (HDPE) that incorporates a layer of coir fibres has been identified to perform multiple functions without compromising the mechanical properties[60]. Modelling studies reveal that when coir mats are associated with rubber mats, synthetic foams and geomembranes can be used as soil reinforcement with appreciable seismic response[61]. However, common practices still aim to enhance the properties of natural fibres by using synthetic chemicals or polymeric resins. The application of natural antimicrobial agents in fibre modification is a recent development in this field[62].

7 Existing Treatment Methods

The critical factors that hinder the performance of LCFs in industrial applications are that they possess less mechanical strength and are highly susceptible to chemical and biological degradation compared to synthetic fibres. Large surface area, hydrophilic nature and basic proteins in natural fabrics provide a suitable niche for biological organisms. Modification methods practised for natural fibres are chosen based on the end use of the fibre. Most of the treatment methods aim to modify the fibre surface. Modifications are done for fibres used in composites to clean the fibre surface and enhance interfacial bonding with the binding matrix[63,64]. Fabrics made from natural fibres such as cotton, wool and jute are modified using toxic-free chemicals or natural agents to impart microbial resistance[65]. These modifications mainly focus on the durability of modified textiles subjected to microbial contact and laundering. Coir and jute geotextiles are generally used in short-term engineering applications and hence are used as such without any modification. The typical treatment processes adopted for fibre modification are discussed below.

7.1 Physical Treatment

Plasma treatment is a dry modification process, mainly employed to enhance the finishing and dyeing stages of textiles made of animal-based natural fibres such as silk, cotton and wool. It is a quick, environmentally friendly process which results in zero waste generation[66]. Corona Discharge Treatment (CDT), commonly adopted in the textile/paper industry, utilizes a strong electric field to alter the polarity of fibres to improve the bonding properties of fibres with the matrix. The treatment is found to be equally effective in plant-based cellulosic fibres[67]. However, the effective depth of penetration is relatively low for physical treatments, which makes this process less attractive for applications that demand a bulk volume of natural fibres.

7.2 Chemical Treatment

Alkali treatment remains one of the most widely accepted methods for surface modification of natural fibres. Aqueous alkaline solutions such as NaOH can alter the orientation of highly cellulose from crystalline to amorphous structure, thus facilitating better penetration of chemicals[68,69]. Alkaline compositions can lead to increased wettability, dispersability, and interfacial strength of fibres embedded in a polymer resin. However, a higher alkaline solution concentration removes the waxy layer of the fibre surface and leads to fibre impairment. At ambient temperature, NaOH concentrations beyond 4 % are reported to reduce tensile strength. At elevated temperatures, alkali treatment can result in fibre degradation and alter the fibre structure[70]. Alkali-steam treatment of fibres is also reported to result in a highly rough fibre surface[71]. The application of alkali activated binders on jute geotextiles is reported to be highly effective in resisting deformations under different slope and rainfall conditions[72].

Silane coupling is a technique adopted to impart resistance to water absorption in natural fibres embedded in a polymer matrix. The hydrocarbon cross-links formed with silane within the fibres check the excessive swelling behaviour of the fibres. Surface modification using stearic acid in combination with ethyl alcohol solution is reported to remove all the non-crystalline constituents from the fibre structure, thus making the surface rough. Stryrene treatment blocks the entry of water into the fibre and improves the polymer-fibre bonding[73]. Potassium permanganate treatment of LCFs pretreated with a suitable alkali enhances the bonding characteristics of such fibres embedded in polymer matrix[74]. Copper sulphate in combination with sodium carbonate can impart superior structural properties to jute fibres, along with rot resistance[75]. Triazine derivatives have multifunctional groups in their structure. Treatment of cellulosic fibres with such compounds ensures cross-linking between the cellulose through hydrogen bonds, thereby leading to a stable binding of the fibre with the polymer matrix at the interface. Isocyanate treatment also imparts better bonding with the matrix[68]. Coir geotextiles modified using lime and silica fumes have been reported to be effective in stabilising expansive soil[76]. Application of chemicals, such as oxalic acid, are capable of enhancing the mechanical properties of coir geotextiles when used for pavement stabilisation[77].

Natural fibres undergo degradation by the attack of macro-organisms such as termites. Termite-resistant coating compositions, which can be applied to natural fibres, can be derived from similar studies on cellulosic materials such as wood. Chemical insecticides such as acetic anhydride, chlorpyrifos, and furfuryl alcohol commonly achieve termite control for wood[78]. However, most of these chemical insecticides pose serious health risks. Treatment with essential oils such as cassia oil and wood tar oil is an environment-friendly option to resist fungal and termite attacks on wood specimens[79].

7.3 Biological (Enzyme) Treatment

Microbial degradation of natural fibres mainly arises due to the action of enzymes released by fungi. Fungal pretreatments are widely carried out to harvest sugars from lignocellulosic biomass. Enzymes are available in numerous varieties, and the selection of enzymes largely depends on the fibre components. Certain enzymes selectively act upon lignin in the fibre and degrade it. Surface modification of cellulosic textile fibres is commonly carried out using enzymes cellulase and hemicellulose[80]. Enzymes successfully enhance the interfacial adhesion, wettability and thermal stability of natural properties[71,81]. However, enzyme treatment is not commonly adopted due to the sizable expenditure involved in the process.

7.4 Physico-Chemical Treatment

Monomers such as ethylene dimethyl acrylate (EMA), 2-Hydroxyethyl methacrylate (HEMA) and acrylamide monomer (AA), when applied on coir fibres in the presence of UV, are reported to result in better mechanical properties[45,82,83]. Monomer application on alkali pretreated coir fibres subjected to UV ageing has a profound influence on the tensile strength, failure strain and the Young's modulus of fibres[84]. The removal of surface imperfections by alkali treatment followed by UV polymerisation enhances the penetration of monomer into the pores of the fibre. This creates a mechanical interlocking of the monomer through the fibre pores, resulting in higher tensile strength. Though UV grafting with monomers is an expensive technique, it considerably enhances coir fibres' mechanical properties.

7.5 Surface Coatings

Coating the fibre/geotextile surface with water repellent coating compositions such as synthetic resins or polymers is a conventional approach. This method aims to arrest the moisture intake by the fibres primarily by physical action, thus resulting in a longer life span of fibres. In a field study conducted for the shore protection of an estuary in India, jute geotextiles coated using bitumen have been reported to develop an extended life of about four years under actual field conditions[56]. However, the possibility of leachate formation has not been investigated in the study. In an experimental study, jute geotextiles treated with bitumen emulsion are found to develop better internal structure and a lower brittleness index[85]. Alkali pretreated sisal geotextiles coated with bituminous emulsion possess a smooth surface, better adhesion and a lesser friction angle[86].

Most conventional modification methods reported to be effective in modifying the fibre behaviour utilise chemicals that tend to trigger environmental pollution[42]. In the effort to foster sustainable techniques, numerous environment-friendly methods for the preservation of lignocellulosic materials have been attempted by researchers. Many natural coating agents with comparable properties to those of synthetic products have been reported to be successful in surface modification of fibres. Coating with natural rubber latex is one such approach. Latex makes the coir fibre resistant to water intake and biological attack by forming a defensive coating on the surface[25].

Antimicrobial compositions based on natural products are now largely applied in textile finishing[87]. Herbal extracts and natural agents such as neem (*Azadirachta indica*), chitosan, aloe vera (*Aloe barbadensis*, Miller) extract, eucalyptus (*Eucalyptus radiata*) oil and tea tree (*Melaleuca alternifolia*) oil are some among those compositions which impart toxic-free antimicrobial, insect repellent finish to fabrics. They display distinct mechanisms such as inactivation of enzymes, binding with proteins, substrate deprivation, complex formation with the cell wall and metal-ion complex formation[88]. Certain plant-derived natural products are identified to possess the capacity to hinder termite attack[89].

Surface modification of cotton fibres using solutions and emulsions of vegetable oils (soybean oil, coconut oil, rapeseed oil, and olive oil) has also been attempted by researchers. Triglycerides in vegetable oils react with cellulose in natural fibres, resulting in the development of hydrophobic long acyl chains which are covalently bonded to the cellulose. The solutions with a higher degree of unsaturation can result in better hydrophobicity. The higher the unsaturated fatty acids in the oil, the better the cross-linked networks in the fibre structure, leading to better crystallinity, higher tensile strength and reduced degradation rates[90]. Chitin and chitosan derivatives are known to possess a high level of antimicrobial resistance. Cotton fabrics modified with chitosan-based finishing have been reported to enhance fabric durability[91]. Cotton fabrics cross-linked using herbal extracts of tulsi leaf, chamomile, sage and green tea are found to develop a high degree of anti-microbial properties[92,93]. However, significant studies on fibre/fabric modifications using such natural products on a large scale are seldom available in the literature. Neem (*Azadirachta indica*) and its products such as neem extract and neem seed oil are known for their medicinal properties, including fungal, bacterial and insect resistance. Neem seed extract has a profound impact on imparting antibacterial properties on polyester/cotton blend fabric[94]. Identical attempts have been carried out on coir and jute geotextiles. Jute fibres and geotextiles treated using neem oil and plant tannin have been identified to develop hydrophobic groups without compromising fibre flexibility[40]. Jute geotextiles coated using a combination of two natural agents, soap nut and turmeric, are reported to exhibit high resistance against degradation when compared to untreated and chemically treated geotextiles[95].

Cashewnut Shell Liquid (CNSL) is a cheap antimicrobial agent with excellent water repellence and flexibility. CNSL obtained by thermal extraction is known as technical CNSL. It polymerises and forms thin layers on surfaces such as wood, coconut thatch, etc., when dispersed in ideal solvents[96]. CNSL-based compositions possess excellent resistance to water absorption, chemical reactions, termite attacks and microbial interferences[97]. Hence, these compounds find vast scope in being utilised as ingredients in paints and varnishes, brake-linings, wood coatings, printer inks and laminating resins[98]. CNSL dispersed in suitable solvents are reported to form excellent surface coatings on lignocellulosic materials such as wood, coconut leaves, coir and jute. Fungal and termite resistance of CNSL-based formulations applied on wooden surfaces has been extensively studied[99]. Coir fibres and yarns modified using a composition of CNSL exhibit superior properties when compared with unmodified coir[41]. The common treatment methods adopted for the modification of natural fibres and the relative advantages and disadvantages of these methods as inferred from the published literature are briefly presented in Table 1.

8 Major Challenges in the Application of Natural Antimicrobial Agents

Antimicrobial activity of natural coating agents on textile substrates of natural origin has been largely researched. The reports on integrating natural

Table 1 — Comparative analysis of various treatment methods for natural fibres

S. No.	Treatment method	Relative advantages and disadvantages	References
I	Physical treatment		
i	Plasma treatment	Quick and environment-friendly process, makes fibre hydrophobic, but can adversely affect mechanical properties	66
ii	Corona discharge treatment	Improves the interfacial compatibility of fibres with the matrix. But penetration into the three-dimensional structure of fibres is not appreciable	67
II	Chemical treatment		
i	Alkali treatment	Economical & less harmful, increase in tensile strength is marginal. Higher concentrations give better results, but the process is not human-friendly	68,69
ii	Alkali-steam treatment	Fibre retains flexibility, but requires high temperature (125 °C). Some portion of lignin re-polymerises during cooling	70,71
iii	Chemicals	Effective in altering the fibre surface properties. In general, most chemicals are costly and harmful to the environment. E.g., chlorophyrifos, benzoyl chloride, acetic anhydride, acrylamide	68,73,77,82,95
iv	Enzymatic treatment	Modifies the surface of fibre but the interior of the cell wall remains unaffected. Increases wettability, but the crystallinity increase is only marginal. Process is costly. E.g., laccase	81
III	Surface coatings		
i	Bitumen	Reduces the hydrophilicity of the fibre, but affects flexibility & drapability. Expensive, acts as a potential source of toxic leachates	56
ii	Natural products (Neem oil, CNSL)	Non-toxic and expensive. Mostly insoluble in water, and hence, attachment with textile substrate requires special pretreatment techniques	25,41,88

antimicrobial agents on lignocellulosic materials such as coconut thatch, wood, wool and cotton fabrics, jute and coir have delivered favourable results[23,41,55,92]. However, the basic mechanism of anti-microbial action of most of these natural agents when subjected to environmental interactions remains undefined.

The commonly available natural antimicrobial products, such as aloe vera, chitosan, curcumin, tea tree oil, and neem oil, are highly expensive and are unavailable in large quantities. Geotextiles have a large surface area and hence require a large quantity of coating agents for surface modification[56]. Although thermosetting polyester coatings and natural resin coatings lower the water intake by the natural fibres and extend their useful life, the reduced wettability and detachment of coatings remain the major challenges. Debonding of fibre surface coatings can occur under certain environmental conditions. The debonding issues can be overcome to some extent by adopting suitable pretreatment techniques such as alkali treatment.

Interfacial bonding of the coating composition with the natural fibres also assumes great significance in long-term applications. Hence, the compatibility of coating compositions using such materials with natural fibres and their stability under practical conditions is to be investigated thoroughly. Further, coating on the fibre has to be carried out using simple techniques as a sizeable volume of geotextiles will have to be handled in the actual field applications. Detailed investigations on surface modification and strengthening of natural fibres for geotechnical applications using natural materials are to be carried out before introducing large-scale processing.

9 Conclusion

A comprehensive literature review is presented concerning the structure and composition of natural fibres and the multitude of factors influencing their durability. The study covers degradation analyses of natural geotextiles, the necessity for modifications, and an overview of the prevalent treatment methods. The current advancements in this field have been subjected to critical analysis. Despite the considerable promise of abundantly available natural fibres in tropical regions to address geotechnical engineering challenges, their widespread utilisation is hampered by their susceptibility to rapid biodegradation under certain environmental conditions. A thorough understanding of the chemical composition, surface properties, and intended applications of natural fibres is paramount.

Most of the conventional surface modification techniques for natural fibres have been designed for applications in composite manufacture. The modifier materials in such cases are synthetic chemicals, and the possibilities of moisture contact, and the leaching of the modifier material are not common, as the fibres are embedded in a polymer matrix. More ecofriendly processes focus on using natural antimicrobial agents, mostly for enhancing fabric properties. Deriving the aforementioned methods for fibre modification applications in the field of geotechnical engineering demands further investigation into the expense and the availability of modifier materials, as well as their environmental impact. From the reported studies, it can be assimilated that there is a need to devise an economical, environment-friendly technique which can increase the life expectancy of natural fibres/geotextiles while maintaining the key properties. As large quantities of geotextiles are employed in actual field applications, the modifier material should be less expensive, readily available, easily processable and environment-friendly. In the interest of sustainability, the selection of locally available natural polymers with antifungal properties can be preferred for surface modification of the natural fibres/geotextiles for geotechnical engineering applications. This is a multi-disciplinary area with a vast extent of field applications and an immense scope for research. Due to their cost-effectiveness, local availability, and reduced carbon footprint, natural fibres/geotextiles with an extended useful life can be a superior alternative to synthetic fibres/geotextiles for long-term engineering applications.

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