Tanzania Journal of Engineering and Technology 2023, **42(2)**: 250-265

Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v42i2.916

Regular Research Manuscript

Review on Modifications of Sisal Fibers for Textile Applications

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ABSTRACT

Properties of sisal fibers such as high coarseness and poor drapability made the fibers less suitable in production of conventional textiles compared to synthetic fibers. The environmental consciousness and depletion of petrochemical resources have attracted researchers on investigating the use of natural fibers in the industrial production of conventional textiles. Sisal is among highly researched natural fibers due to its features such as strength, recyclability, availability, low processing cost, light weight and ease process ability. This paper reviews possible modifications of sisal fibers to enhance performance in conventional textiles applications.

ARTICLE INFO

First submitted: June 29, 2022

Revised: Sep. 29, 2022

Accepted: Mar. 15, 2023

Published: June, 2023

Keywords: *Natural fibers, sisal fibers, modifications and conventional textiles.*

INTRODUCTION

Sisal is one of the natural fibers extracted from the leaves of sisal plant (Biswabhusan et al., 2019; Sujatha et al., 2018). Sisal fiber is a highly pliable material with high aspect ratio (Ferreira et al., 2018a; Peças et al., 2018). Currently, there is a great attention in maximizing the utilization of leaf-based fibers for conventional and technical textile applications because of their sustainability features (Fan et al., 2021; Ferreira et al., 2018b; Adekunle, 2015; Cruz and Fangueiro, 2016; Salit et al., 2015a).

Sisal fibers can be used in textiles for fabrication of upholstery, curtains, doormats, table mats, carpets, lugs and composites for various technical textiles application (Elanchezhian et al., 2018; Naveen et al., 2018; Fiore et al., 2016). However, sisal fibers suffer from some drawbacks such as coarseness and higher hygroscopic nature. The coarseness causes poor draping and poor handle when formed into fabric, which limits its application in apparel. The higher hygroscopic nature of the fiber makes it susceptible to attack by microorganisms when used in moist and warm environment (Oladele et al., 2014). Due to the above-mentioned drawbacks, most of the sisal fiber applications have been replaced with synthetic fibers. Synthetic fibers can be produced into any desired fineness, hence can be woven into fabrics with high drapability and appealing handle. In addition, synthetic fibers are highly hydrophobic, hence are not easily

attacked by microorganisms. However, the use of synthetic fibers is challenged because they are derived from nonrenewable resources with significant environmental footprint (Chauhan et al., 2022). Several studies on the modification and utilization of sisal fibers for textiles applications have been reported in order to address the environmental challenges of the synthetic fibers. Nevertheless, major research focus has been on modification of sisal fibers for making composites for technical textiles applications. Similar efforts are required for the modification of sisal fibers in conventional textile applications. This
will not only add value but also increase economic opportunities along the supply chain of the sisal fiber.

Extraction of Sisal Fibers: Sisal fibers can be extracted from the plant leaves via retting or mechanical methods. Retting involves extraction of the fibers from sisal leaf through degradation of the cementing material which surround the fibers by either chemical or biological means (Summerscales et al., 2010). Chemical retting involves boiling of the plant leaves with chemical reagents such as sodium hydroxide or sodium benzoate which facilitate the degradation of non-cellulosic material (Sadrmanesh and Chen, 2019). Biological retting involves the use of enzymes which are naturally secreted by micro-organism due to exposure of plant leaves in moisture or soaking in water for several days (Summerscales, 2021). Due to advancement in biotechnology, the biological retting can be controlled through the use of commercially available enzymes such as pectinase (Tahir et al, 2011). In the mechanical extraction method, the process is achieved through tearing of the plant leaf to detach the fibers from the cementing materials and this process is facilitated by the use of machines such as decorticator (Naveen et al., 2018; Salit et al., 2015b; Santos et al., 2015). The strength and weaknesses of various methods used for extraction of sisal fibers are reported in the literature, Table 1.

Table 1: Strength and weakness of sisal fiber extraction methods

Extraction method	Strength	Weakness
Chemical retting	Produce fibers with high purity. Enhanced mechanical properties.	Releases effluents to the environment. Requires energy.
Water retting	Produce fibers with high purity.	Releases effluents to the environment. Inconsistence in fiber quality.
Enzymatic retting	Saves time. Convenient method. Consistence in fiber quality.	Poor fiber strength.
Mechanical	High productivity.	Costly. Produce highly variable fiber length. Produce fibers with high impurity.

(Summerscales, 2021; Sadrmanesh & Chen, 2019; Liu et al., 2017)

Properties and Applications of Sisal Fibers: The chemical composition, physical and mechanical properties of sisal fibers vary depending on origin, age and plant location (Ibrahim et al., 2016). Chemically, sisal fiber is composed of cellulose, hemicellulose, lignin and moisture as indicated in Table 2. Good mechanical properties attracts use in different textiles applications especially in areas which demand high mechanical strength (Shahzad et al., 2022; Getu et al., 2020; Kumar et al., 2019; Uppal et al., 2019; Sahu & Gupta, 2017a; Senthilkumar et al., 2018). Sisal fibers are also used in packaging and agriculture applications. In packaging industry, sisal fibers are used for making different packages for food products because the fibers are biodegradable and possess good strength that can withstand different conditions of storage, handling and transportation of foods (Ali et al., 2021). Also, the high strength properties of sisal fibers make them suitable in fabrication of ropes and twines for various applications (Sabarish et al., 2020). Additionally, due to good dye uptake properties, sisal fibers are used for making mats, bags, carpet, table mats, door mats and upholstery (Melo et al., 2019; Naveen et al., 2018; Peças et al., 2018; Sahu & Gupta, 2017b ; Basu et al., 2012; Kim & Netravali, 2010). The high cellulose content of the sisal fiber, Table 2 makes it possible for chemical modification to suit in different applications.

Table 2: Chemical composition and properties of sisal fibers

Chemical composition	
Component	**Composition (%)**
Cellulose	60-78
Hemicellulose	10-22
Lignin	8-14
Moisture	10-22

(Naveen et al., 2018; Senthilkumar et al., 2018; Rana et al., 2017; Sahu & Gupta, 2017a)

Physical and mechanical properties	
Property	**Value**
Diameter (μm)	25-200
Density (g/cm^3)	1.45
Tensile strength (MPa)	400-700
Young's modulus (GPa)	9-22
Elongation at break (%)	3-14

(Zhu et al., 2020; Maya et al., 2017; Kalia et al., 2009; Mishra et al., 2004)

Application of Sisal Fibers in Textiles

Uses of sisal in textiles are categorized into conventional and non-conventional applications. Conventional applications include textiles for covering, decorations and aesthetics such as apparels and home furnishing (Umair and Khan, 2020; Elanchezhian et al., 2018; Fiore et al., 2016). Conventional textile products made from sisal fiber suffer strong competition compared to those made from synthetic and other natural fibers such as cotton. This is due to some end use features of sisal fibers such as stiffness, dimensional instability and poor moisture management properties which are inconvenient to some of the applications (Asinyo et al., 2016).

Non-conventional or technical category involves textile applications which are based on the functional requirements. Sisal fibers are utilized as a reinforcing agent in making composites for varieties of technical applications including agro textiles, automotive, aerospace, upholstery, shades, sports, construction and geo-textiles (Umair and Khan, 2020; Uppal et al., 2019; Richaud et al., 2017; Desai and Kant, 2016; Qin, 2016; Prabakar and Sridhar, 2002).

Sisal Fibers Vs Synthetic Fibers

Before WW1 and WW2, the use of natural fibers dominated textiles applications. Following high demand of textile fibers during the WW1 and WW2, research focused on alternative sources of fibers. Therefore, most of the synthetic fibers were invented during the middle of the 20th century (Kithiia et al., 2020; Townsend, 2020; Shahzad, 2012; Cruthers et al., 2009). Synthetic fibers are produced from petrochemicals which are non-renewable. Since the late 20th century, pressure on the depletion of the petrochemical resources and associated environmental footprint encourages the need for natural fibers (Salit et al., 2015b).

Furthermore, synthetic fibers have negative environmental effects since they are non-biodegradable thus attract needs for further research in natural fibers to replace the synthetic ones (Uppal et al., 2019; Balakrishnan et al., 2016). Sisal is among the most researched leaf fibers in the efforts to replace synthetic fibers (de Klerk et al., 2020; Naveen et al., 2018; Senthilkumar et al., 2018; Kumre et al., 2017; Sahu and Gupta, 2017a; Ibrahim et al., 2016). Research has been conducted on physical and chemical modification of sisal fibers for technical applications. However, research information on modification of sisal fibers for non-technical applications such as apparels and home furnishing products is limited. Since sisal fibers are cellulosic polymers, any chemical or physical modification of cellulose structure can result into modification of sisal fiber.

DISCUSSIONS

Modification of Sisal Fibers for Conventional and Technical Applications

The purpose of fiber modification is to improve or impart new properties for specific application. The modification of sisal fibers can be done through physical, chemical or biological methods. In some cases, more than one method can be applied depending on the targeted properties. Modification of sisal and related cellulosic fibers for textiles applications has been extensively researched and reported elsewhere (Evans et al., 2015; González et al., 2015; Haule et al., 2012; Ristić et al., 2009; Alvarez and Vázquez, 2006; Mitchell et al., 2005; Shekarriz et al., 2003; Mccord et al., 2002; Battistel et al., 2001; Buchert et al., 2001; Johansson et al., 1999; Benerito et al., 1981). The modification methods which can add value in sisal fibers and positively boosts the efforts of intensifying its utilization in varieties of applications are discussed in the subsequent sections.

Physical modification method

Physical modification involves the change in the physical structure and surface properties of fiber without affecting its chemical structure (Adekunle, 2015). Physical modification involves altering either the fiber outer surface, form of the unit cell, cross-section area or supramolecular structure by spinning, drawing, crimping and relaxation treatment.

The most common physical modification techniques include corona treatment, plasma treatment, ultrasound treatment, ultraviolet radiation and alkalization. Although most of the physical modifications can be done through chemical treatments, the use of chemicals is discouraging due to its sustainability challenges. The physical modifications are reported to improve physical features of the fibers to suit into conventional and non-conventional textiles applications. Additionally physical modifications are reported to aid in purification of cellulosic fibers as well as activating the surface properties of fibers (Belgacem and Gandini, 2005).

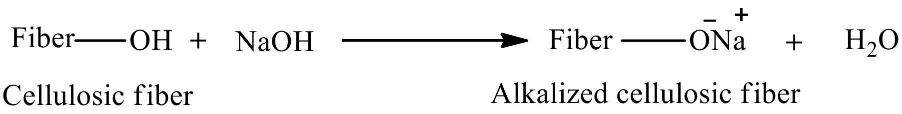
Corona treatment technique works under atmospheric pressure and uses air as a reagent. The ionized air hits the fiber surface and causes oxidation of the fiber molecules thus increasing polarity and activation of the surface properties of fibers to enable application of different finishes (Izdebska, 2015; Shishoo, 2007). Due to increase in the polarity, the wettability of the material increases. The hitting eliminates the weakly bounded impurities, which affects adhesion properties of the fiber hence the fiber is imparted with textural change. Also the elimination of impurities enhance forces of attractions hence improved mechanical properties of the fiber (Ferreira et al., 2018b; Ragoubi et al., 2010; Pizzi et al., 2009; Gassan et al., 2000).

Plasma treatment is similar to the corona treatment except in plasma treatment the substrate interacts with the ionized gas (Cruz and Fangueiro, 2016). Plasma treatment allows modification of the composition of plasma through injecting different gases based on the intended end use (McKeen 2016).

Ultrasound treatment involves application of sound energy to generate pressure and temperature on the fiber surface thus altering the morphological, chemical and mechanical properties (Ferreira et al., 2018b; Mukhopadhyay and Fangueiro, 2009). Ultrasonic vibrations create cavitation bubbles which implode, cause the sonication reactions and form the micro flows which penetrate easily on the surface of the material thus increases the efficiency of modifications process (Qasim et al., 2018; Liu et al., 2007). The ultrasonic treatment on cellulosic fibers are reported to purify the fibers through rupturing of the weak boundary layers of lignin and hemicellulose (Kumar and Sharma, 2017; Mukhopadhyay and Fangueiro, 2009). Ultrasound treatment can be used in combination with other treatments such as chemical or enzyme treatments to enhance the properties of the fibers. The combination of alkaline and ultrasound treatment in sisal fibers are reported to reduce the hydrophilic properties, improve mechanical properties and thermal stability of the fibers (Krishnaiah et al. 2017, 2018; Dittenber and Gangarao 2012) .

Ultraviolet treatment involves irradiation of the fibers with the wavelength ranges from 10 to 400 nm which facilitates photo initiation reactions (Ferreira et al., 2018a). Treatment of sisal fibers with ultraviolet radiation facilitates graft co-polymerization for improved mechanical properties (Khan et al., 2007) Moreover, ultraviolet treatment in cellulosic fibers is reported to modify the fiber properties through eliminating the non-cellulosic materials. Furthermore, ultraviolent treatment imparts wettability properties, increases strength and polarity properties of the fibers (Khalid et al., 2021; Liu et al., 2017; Mukhopadhyay and Fangueiro, 2009).

Alkalization treatment changes the orientation of the cellulose unit cell and the magnitude of the hydrogen bonding network, which results in change in the form of the unit cell. In alkalization treatment the fibers are immersed in alkaline solution preferably sodium hydroxide at a given concentration, temperature and time. Alkalization causes the disruption of hydrogen bonds in cellulosic fibers thus promotes the ionization of the hydroxyl group to the alkoxide, Scheme 1 (Jena et al., 2022). Also, the alkalization process exposes the surface of cellulose through eliminating the non-cellulosic materials such as pectin, wax, lignin, hemicellulose and fatty materials (Kalia et al., 2009). Alkalization of cellulosic fibers reduces stiffness, improves mechanical properties and accessibility by reagents (Kithiia et al., 2020; Haule et al., 2014). Alkalization process is affected by several factors including concentration of alkaline solution, temperature and time. These parameters are reported to be used differently by several authors ranging from 2% to 30% (W/V) of sodium hydroxide, at temperature range of 20 °C to 120 °C and time range of 30 minutes to 48 hours (Sahu and Gupta, 2020; Pickering et al., 2016; Hajiha et al., 2014; Kaushik et al., 2013; Kabir et al., 2012; Kim & Netravali, 2010; Li et al., 2007a). Generally, the alkalization process is reported to increase the thermal and mechanical properties of cellulosic fibers (Tanasă et al., 2020; Sahu & Gupta, 2019; Siakeng et al., 2019; Kumar and Sharma, 2017; Reddy et al., 2013). However, treatment beyond the optimal range can cause defects on the fibers. Thus, probably there is a need for establishing the optimal treatment parameters for the alkalization of sisal fibers for the technical and also non-conventional textile-based applications.



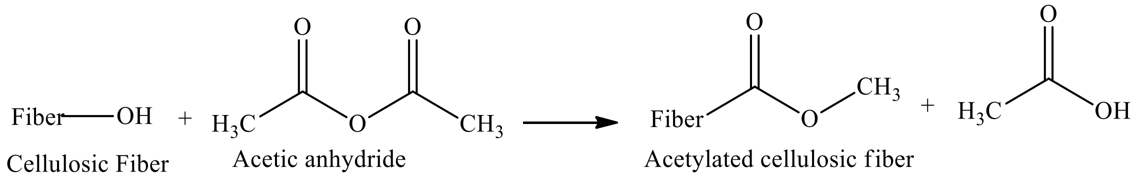
Scheme 1: Alkalization reaction.

The discussed physical treatment techniques are used for pretreatment by either removing the impurities from the fiber surface, altering the surface texture or enhancing surface reactivity for ease of chemical modification.

Chemical modification methods

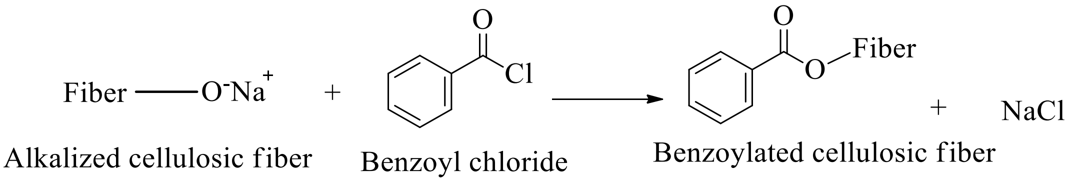
Chemical modification methods allow possibility in engineering of the fibers by imparting functional groups for enhanced specific applications. Certain properties of fiber can be controlled though chemical modification. Properties of sisal fibers such moisture absorption, strength and drivability can be controlled to suit certain applications through modifying the fiber parent structure (Radoor et al., 2020; Kaushik et al., 2013). Taking the advantage of reactive groups of sisal fibers (-OH groups), different functional groups can be introduced to the fiber structure through the hydroxyl group reactions such as esterification, etherification and coupling. Hence the fiber properties can be modified depending on the nature of the introduced group. For example, high hydrophilic properties of sisal fibers are due to strong interactions between OH group of fiber and water through hydrogen bonding. Therefore, any functional group introduced to the fiber structure which will result into minimizing the OH groups will end into lowering the fiber's hydrophilic nature.

Esterification (acetylation) is the common method for reducing the hydrophilic properties of cellulosic fibers. The acetylation reaction (Scheme 2) induces hydrophobic properties on cellulosic fibers through displacement of hydroxyl group of cellulose with an acetyl group as a result it reduces the swelling tendency (Adekomaya and Majozi, 2019; Ferreira et al., 2018a; Siakeng et al., 2018; Ibrahim et al., 2016; Hajiha et al., 2014).



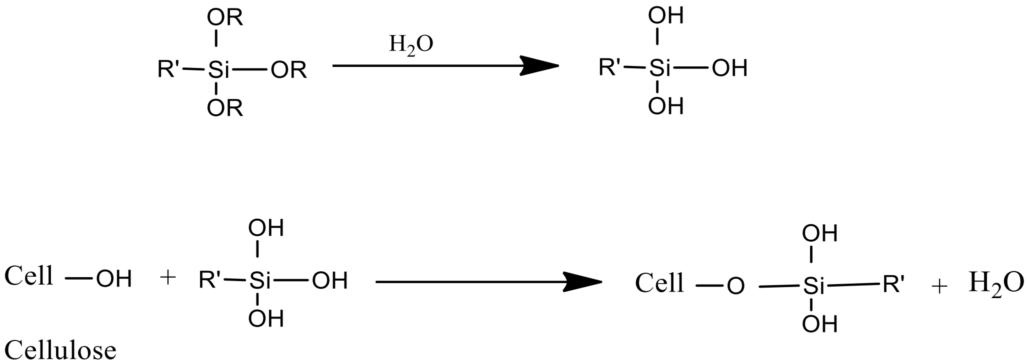
Scheme 2: Acetylation reaction.

Similarly, benzoylation reaction involves the replacement of the hydroxyl groups of cellulosic fibers with the Benzoyl group mostly from the benzoyl chloride or benzoyl peroxide (Kabir et al. 2012). Benzoylation reaction reduces the hydrophilic tendency of cellulosic fibres and improves the thermal stability property of fibres due to the introduction of the aromatic ring (Thyavihalli Girijappa et al., 2019; Elanchezhian et al., 2018; Naveen et al., 2018; Kaushik et al., 2013; Yuan et al., 2013). For effective benzoylation, the fiber must first be treated with alkaline solution in order to activate the functional group then followed by the treatment with benzoyl chloride, Scheme 3 (Tanasă et al., 2020; Li et al., 2007a) .

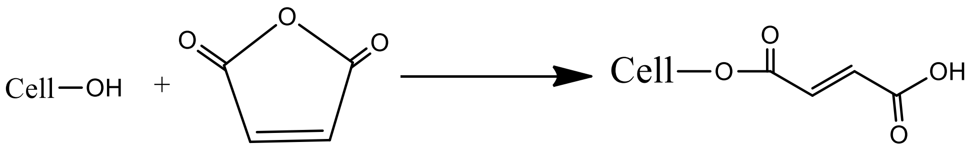


Scheme 3: Benzoylation reaction.

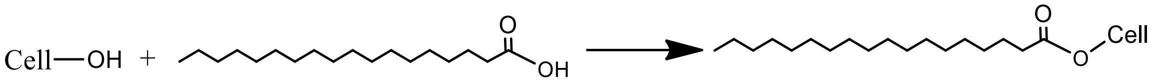
Coupling agents are compounds which possess bifunctional groups thus act as a cross linkers in holding together two dissimilar materials. For instance, coupling agents can bind cellulose with other chemical finishes (Mallakpour and Madani, 2015; Hajiha et al., 2014). The commonly used coupling agents in cellulose modification are silanes, isocyanates, multi-functional carboxylic acids and titanate-based compounds. Silane is the mostly used coupling agent, it induces the hydrophobic properties to the cellulosic fibers due to the presence of high hydrophobic alkoxy group as well as the high affinity of silanol towards the polar functional group of the cellulose (Ferreira et al., 2018b; Hajiha et al., 2014; Xie et al., 2010; Kalia et al., 2009; Li et al., 2007b). During treatment, the silane coupling agent is firstly hydrolyzed to form reactive silanol group which later condenses to forms alkoxy linkage with the cellulose, Scheme 4. Thus reduces the swelling tendency of the fibers and creates bridge between the cellulose and other chemicals (Xie et al., 2010). Additionally, silane observed to improves the mechanical strength and thermal stability properties of sisal fibres. This is due to the nature of the bonding as well as presence of silica which is inert in nature and thermally stable (Gun'ko, 2018; Głowińska et al., 2017). Maleic anhydride is among the most efficiently used coupling agents, it possesses the dicarboxylic functional groups which can create bridge between cellulose and other chemicals to enhance a certain property onto the fibers, Scheme 5. It has been reported that, the treatment of sisal fibers with maleic anhydride results in increased tensile strength, flexural modulus and reduction in moisture absorption properties of the fibers (Ibrahim et al., 2016; Kalia et al., 2009). Also, treatment of cellulosic fibers with steric acid eliminates the non-crystalline constituent as well as increase the fibrillation of the fibers (Khalid et al., 2021). Steric acid reacts with polar group of cellulosic fibers through esterification reaction (Scheme 6) thus reduces the hydrophilic properties of the material and enhances mechanical strength of the fibers (Kabir et al., 2012). Generally, coupling agents allow modification of cellulosic fibers with different chemicals to achieve different properties.



Scheme 4: Reaction mechanism of silane coupling agent with cellulosic fiber



Scheme 5: Reaction mechanism of maleic anhydride with cellulosic fiber



Scheme 6: Reaction mechanism of steric acid with cellulosic fiber.

Biological modification

Biological modification involves the use of greener reagents and low energy technology in modifying the surface properties of fibers for an intended performance (Darie-Nita et al., 2022). Biological modification is considered to be ecofriendly compared to chemical and physical modification methods because it involves the use of secretions from microorganism and the modified material capable of biodegrading on its disposability (González et al., 2015). The biological modifications improve the surface properties of fibers for various applications through the use of enzymes or bacterial secretions (Boey et al., 2022; Saha et al., 2012). Enzymes are either produced commercially or *insitu* secreted by fungi and bacteria.

Enzymes are most preferred in modification of natural fibers since they are specific in performing the intended function (Norrrahim et al., 2021; Faruk et al., 2012). Treatment of cellulosic fibers with enzymes improves softness, drapability, luster and moisture absorption properties (Shiresha Manyam et al., 2018; Zwane et al., 2019). In some situations, combination of chemical and enzyme treatment is more effective than enzymes alone. For instance, treatment of sisal fibers with combination of alkaline solution and laccase enzymes have been very effective on improving properties of the fibers (Peng et al., 2010).

The major drawbacks associated with biological modifications methods are inconsistence, difficult in reproducibility especially for commercialization and they are time consuming. Therefore, there is a need of establishment of optimized parameters for efficient, consistence and reproducibility of biological modified materials.

Conclusion and Future Outlook

The utilization of sisal fibers for both conventional and non-conventional or technical textiles applications could be maximized through the structural and surface modification of the fibers. The sisal fiber properties can be modified through chemical, physical and biological methods. Thus, with different modifications techniques it is possible to improve or introduce new properties to suit specific applications. This suggests that the limitations of use of sisal fibers which led to replacement with synthetic fibers for some textile applications can be controlled through the discussed modification techniques. Furthering research on the modification of sisal fibers for conventional and non-conventional textile application is the superlative avenue for overcoming the challenges associated with the use of non-renewable synthetic fibers in similar application.

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