

NATURAL FIBERS AS SUSTAINABLE BIOMATERIALS FOR SUTURE AND CATHETER APPLICATIONS

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ABSTRACT

As the need to create safe, biocompatible, and environmentally friendly biomedical materials increases; so too does the interest in using natural fibers for both sutures and catheters. Natural fibers obtained from animals, plants, microbes, and marine life provide unique benefits such as being renewable, biodegradable, biocompatible, having advantageous mechanical properties, and providing opportunities for biological functionalization. In this review, we examine the use of natural fibers as sustainable biomaterials in the creation of sutures and catheters. We focus on how these fibers are sourced, their chemical and physical-chemical attributes, their mechanical performance, their rate of biodegradation, and their biological attributes. We discuss some of the most common types of natural fibers used in biomedicine (collagen, silk fibroin, chitosan, alginate, cellulose, bacterial cellulose, cotton, flax, and hemp) and how they could potentially be utilized in sutures and catheters. We also look at different ways that natural fibers can be modified or functionalized to overcome some of their limitations. Modifications include cross-linking, blending with other polymers, coating them with other substances, electrospinning them, incorporating nanoparticles into them, and making composites out of them. Additionally, we describe the manufacturing and processing methods used to produce natural fiber-based biomaterials; how they can be sterilized; and what some of the challenges associated with producing consistent batches of natural fiber-based biomaterials are. Finally, we highlight several areas where there have been recent developments in smart materials, antimicrobial systems, drug eluting devices, and composite materials made of natural fibers and synthetic polymers. These developments illustrate the potential for creating multifunctional biomedical products with the help of natural fibers. Ultimately, natural fibers have the potential to serve as sustainable bases upon which researchers will continue to develop new suture and catheter technology with greater functionality, biocompatibility, and environmental friendliness.

KEYWORDS: Natural fibers; Sustainable biomaterials; Sutures; Catheters; Biodegradability; Biocompatibility; Silk fibroin; Cellulose; Chitosan; Nanofibers; Drug delivery; Biomedical devices.

1. INTRODUCTION

1.1 Background of Sutures and Catheters

Sutures and catheters represent two of the most common medical devices utilized in support of surgical interventions, closure of wounds, drainage of fluids, administration of drugs, and monitoring of patient functions. Sutures function to approximate and hold together tissue edges throughout the course of wound repair; whereas catheters allow temporary or permanent access to anatomical areas for either the delivery or removal of fluid and/or therapeutic agents. A suture with optimal performance would have sufficient tensile strength, flexibility, adequate knot holding ability, appropriate handling properties, and produce little to no tissue reaction while retaining its mechanical properties throughout the required healing time [1]. An optimal catheter will incorporate flexibility, mechanical strength, surface smoothness, chemical stability, biocompatibility, and resistance to adherence and formation of biofilms [2].

The manner in which the implantable device interacts with living tissue is greatly dependent upon the type of material used to create the device and the way that the surface has been prepared. After an implantable device has been placed into the body, there will be interactions between the proteins, cells, micro-organisms and inflammatory mediators present in the surrounding tissues and the surface of the implantable device. Thus, selecting appropriate biomaterials is essential to reduce the likelihood of complications arising from the placement of the implantable device including inflammation, infection, thrombosis, tissue injury and prolonged recovery periods. Due to the need to meet these criteria, there has been a steady increase in the number of new biomaterials developed that provide the necessary structural properties along with beneficial biological responses [3].

Evolution of Biomaterials in Suture and Catheter Development

The development of suture and catheter materials is moving away from using natural materials to using increasingly engineered synthetic polymers and composite systems. Examples of traditional suture materials included silk, cotton, linen, and catgut; additionally, collagen-based materials had early promise due to being biologically based and degradable [4]. As polymer science advanced, synthetic materials such as nylon, polypropylene, polyester, poly(glycolic acid), poly(lactic-co-glycolic acid), polyurethane, silicone, and poly(vinyl chloride) were developed and adopted because they provided improved control over the mechanical properties, degradation rates, flexibility, and processing characteristics of these products.

The development of catheter materials has focused on the properties of flexibility, strength, lubricity, and chemical resistance. Materials that meet these requirements include silicone, polyurethane, polyvinyl chloride (PVC), polyethylene (PE), and fluorinated polymers [5]. However, as the knowledge about host-material interaction increases, so too does the shift in biomaterial development from purely mechanical considerations to the creation of multi-functional systems that incorporate biocompatibility, anti-microbial activities, controlled degradation, and tissue integration.

Limitations of Conventional Synthetic Materials

In spite of being superior technologically, there are many disadvantages associated with synthetic materials. Synthetic polymers allow for high mechanical strength and consistent production; however, the ability to control the biological performance of these materials is dependent upon the chemical structure, the surface properties, the degradation mechanism, as well as the processing additives used during manufacture. There are numerous factors that will affect the material's performance in suture applications including bacterial adherence, inflammatory response, tissue reaction and wound healing. Studies comparing various types of sutures have shown that there can be significant differences in both the rate of bacterial colonization and tissue irritation among commonly utilized suture materials, demonstrating the need for appropriate material selection [1].

Catheter material limitations also exist in the form of microbial attachment; biofilm development; thrombus development; friction; and irritation of surrounding tissues. Catheter related infections continue to be a large problem clinically due to the ability for microorganisms to adhere to the catheter surface and form protective biofilms which are hard to remove once developed [2]. Some existing catheter materials may also need to be modified on the surface or have antimicrobial coatings applied to enhance the material's biological function. In addition to this, most of today's conventional polymer materials are produced either entirely or partially using feed stocks that are derived from fossil fuels. This creates more concern over dependency upon resources, waste production, and how long the materials will last in the environment. These limitations have prompted researchers to look into alternative methods of producing renewable, biodegradable, and biologically active alternatives [6].

Emergence of Natural Fibers as Biomedical Materials

The inherent biological functions of natural fibers and natural biopolymers make them very attractive as potential alternative or supplemental materials in biomedical applications. They also offer a renewable source, are biodegradable, and provide the opportunity to be structurally modified [7]. Examples of such materials are collagen, silk fibroin, chitosan, alginate, cellulose, as well as many additional proteins- and polysaccharides-based materials. Materials from these sources contain functional groups and molecular structures that may interact with cells, proteins, and ECM (extracellular matrix) components, thus providing opportunities for the support of tissue repair and regeneration [7] [8].

Among the various materials used in this study, Collagen is similar biologically to human connective tissue; Silk Fibroin has great mechanical properties as well as good biocompatibility; Chitosan has biodegradable properties and is also antimicrobial and hemostatic [8]. Cellulose and its derivatives have many benefits including being abundant, renewable, having good mechanical properties, and can be made into fibers, films, membranes and nanostructured materials [7]. These features make natural fibers extremely promising for developing sutures, catheter coating, strengthening structures and developing multifunctional biomedical devices.

Sustainability and Environmental Significance

The growing need for more sustainable materials is driving research into natural fibers to create medical devices. Natural biomaterials are created using renewable biological sources and, based on their composition and how they are processed, have potential to provide enhanced biodegradability as well as reduced reliance upon fossil fuel-based raw materials [7]. Research in sustainable polymers is focused more and more on obtaining raw materials through sustainable means, using efficient processes, responsibly managing the end-of-life of products, and reducing negative environmental effects throughout the entire product lifecycle [8].

Sustainability of biomedical materials is not determined simply by whether they are natural in origin. Each stage in the production process (cultivation, harvesting, purification, chemical modification, sterilization, packaging, transportation, and disposal) may have an impact on the environment. Thus, when evaluating the sustainability of a material, it is necessary to consider the entire life cycle of the material and not just the natural origin of the material [9].

Rationale and Scope of the Review

As the need for biocompatible, functional, and environmentally friendly medical devices increases so does the justification to explore natural fibers as potential suture and catheter materials. Natural fibers provide many advantages including biological compatibility, biodegradability, functional flexibility, and being sourced from a renewable resource, which could possibly provide solutions to some of the limitations of conventional materials [8] [7]. However, there are also numerous limitations associated with mechanical properties, variability, manufacturing, sterilization, controlling degradation rates, and converting research into clinically relevant products.

Therefore, the present review provides a comprehensive analysis of the potential of natural fibers as environmentally friendly, biocompatible biomaterials in both suture and catheter applications, with a focus on their properties, functional capabilities in biological systems, existing uses, advantages, limitations, modifications, and possible future directions. Specifically, the relationship between natural fiber structures, biological performance, mechanical requirements, and environmental impact (sustainability) will be examined to identify promising areas for the development of new generation sutures and catheters [10].

Natural Fibers as Biomedical Biomaterials

Definition and Classification of Natural Fibers

Natural fibers are made from biologically renewable or naturally-occurring sources. They are composed of organized macromolecular structures like polysaccharides, proteins, and other biogenic components. Depending upon where they come from, natural fibers are generally divided into three main groups: plant fibers, animal fibers, and mineral fibers [11]. Plant-derived fibers include flax, hemp, jute, cotton, sisal, ramie, bamboo and pineapple; while animal-derived fibers include silk, wool, keratin-rich fibers, and collagen-based structures. Mineral fibers form another group, however, due to issues with biocompatibility and safety, they are much less relevant to biomedical applications [11]. However, in biomedical engineering, the term natural fiber is often used in a much broader sense to describe any naturally derived fibrous biomaterial or biopolymer system that may be processed into fibers, nanofibers, membranes, scaffolds or composite structures [12].

As a result of their hierarchical structure, chemically active functional groups, ability to be produced from renewable sources, and interaction with living systems; natural fibers are being considered for potential application as biomaterials. Depending upon how the fiber is sourced and processed, it may be utilized alone or integrated with a polymer matrix to create a fiber-reinforced biocomposite [12] [13].

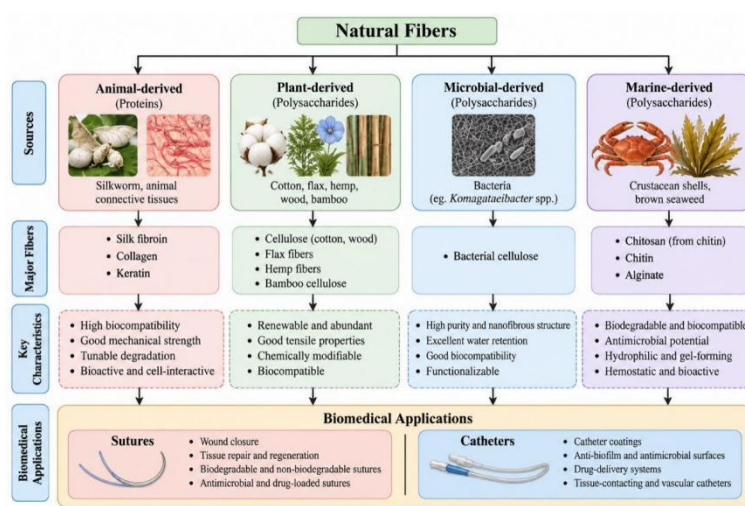


Figure 1. Sources, Classification, and Biomedical Applications of Natural Fibers

Sources of Natural Fibers

There are numerous natural sources of fiber that are derived from various biological materials, including plants, animals, microorganisms, and marine organisms. Of all the different types of biological natural fibers, plant fibers represent one of the largest and easiest to acquire. The botanical source for obtaining plant fibers depends upon where they are located on the plant. Some examples include: bast fibers that come from stems (flax, hemp, jute, ramie), leaf fibers that come from leaves (sisal, pineapple, abaca), seed fibers that come from seeds (cotton), and fibers that come from other parts of plants (grasses, agricultural residues, wood) [14] [11]. The great quantity of options available allows for greater choices when it comes to selecting fibers based on their intended use.

Natural biomaterials can be made using animal-derived fibers. Silk is mostly made with silkworms and contains primarily fibroin surrounded by sericin. Wool and feathers are primarily made with keratin. Collagen is an additional natural biomaterial that comes from animals; it's a structural material that can be found in many types of connective tissue [13], [14]. In addition to animal-derived biomaterials, marine and microbial sources have provided many additional biomaterials that come from nature. Chitosan is produced after treating chitin (which can be found in crustacean shells and other types of biological sources) and alginate is typically taken from brown seaweeds. Bacterial cellulose is produced by certain microorganisms, and has a very interconnected nanofibrous structure [12], [15].

The choice of which type of natural fiber to select for use in biomaterials will depend on several factors including: availability, chemical composition, purity, processing required, mechanical properties, degradation behavior, and the intended biomedical application. As such, the selection of the raw material source is a critical factor in determining the overall performance of natural fiber-based biomaterials [16].

Table 1. Classification and Characteristics of Natural Fibers Relevant to Suture and Catheter Applications

Source	Representative Fibers	Major Components	Key Characteristics	Biomedical Relevance
Animal	Silk fibroin, Collagen	Proteins	High biocompatibility, strength, tunable degradation	Sutures, tissue interfaces, catheter coatings

Animal	Keratin	Keratin protein	Bioactive, cysteine-rich, biodegradable	Sutures, wound-healing systems
Plant	Cellulose, Cotton	Cellulose	Renewable, strong, chemically modifiable	Sutures, catheter reinforcement
Plant	Flax, Hemp	Cellulose, hemicellulose, lignin	Lightweight, strong, sustainable	Composite sutures and catheter structures
Microbial	Bacterial cellulose	Cellulose	High purity, water retention, nanofibrous structure	Catheter coatings, wound materials
Marine	Chitosan, Chitin	Chitin/chitosan	Antimicrobial, biodegradable, hemostatic	Sutures, antimicrobial catheter coatings
Marine	Alginate	Polysaccharides	Hydrophilic, gel-forming, ion-responsive	Drug delivery, coatings, wound systems
Emerging sources	Other bio-derived fibers	Proteins/polysaccharides	Functionalizable and renewable	Advanced biomedical composites

Chemical Composition and Molecular Structure

The biological source of a natural fiber will determine its chemical composition. For example, plant fibers are made up primarily of lignocellulose. In addition to being composed of cellulose, hemicellulose, lignin, pectins, and waxes; plant fibers also have other minor extractive components [13]. Cellulose is a long chain of beta- (1->4) linked D-glucose molecules. These chains organize into two types of regions (ordered crystalline and less ordered amorphous) by forming many intra- and inter-molecular hydrogen bonds. This organization of chains results in an increase in both stiffness and strength in cellulose-rich fibers [14].

The hemicelluloses are a group of heterogeneous, branched polysaccharide molecules which are associated with the cellulose microfibrils in the plant cell wall. They contribute to the spatial arrangement of the components of the cell wall. Lignin is a rigid, hydrophobic, and highly crosslinked aromatic macromolecule which contributes to the physical properties of plants and protects them from microbial attack. Flax, hemp, jute, cotton, sisal, bamboo and many other plant types contain varying amounts of cellulose, hemicellulose, lignin, pectin, and waxes. These variations lead to differences in the chemical, physical and mechanical responses of these materials [11], [14].

Protein fibers produced from animals differ significantly in terms of molecular composition. For example, silk fibroin is composed primarily of proteins with repeating amino acid sequences and crystalline β -sheet regions. These two components provide the fiber with high mechanical strength and stability. In contrast, collagen has a distinctive triple helix structure that provides support for both biological and mechanical functions. Similarly, polysaccharides derived from nature (e.g., chitosan and alginate) have numerous functional groups that allow for chemical modifications, cross-linking, and interactions with biological compounds [12], [15].

Physicochemical Properties

The physicochemical characteristics of natural fibers depend upon several factors including; chemical make-up, crystallinity, molecular structure, surface characteristics, moisture level, and the history of processing. Hydrophilic properties are common among cellulose based fibers due to the high number of hydroxyl groups present in their surface layers [17], [18]. These hydroxyl groups allow the fiber to interact well with water and many different types of polar compounds. This ability to interact with water and polar compounds may provide benefits when used in biological systems that require hydration and interaction with the aqueous solutions found within the body. However, too much moisture absorption will negatively impact the dimensional stability and mechanical performance of the fiber [13], [14].

The significance of surface chemistry lies in the fact that it contains various functional groups including hydroxyl, amino, carboxyl and sulfate which offer positions for chemical modifications, cross-linking, drug attachment and incorporation of biological molecules. In addition to being porous, many natural fibers are hierarchically structured providing an ideal surface for cell attachment and molecule transport [12]. Other properties such as crystallinity, thermal stability, swelling behavior, surface energy and degradation rate will influence whether a particular fiber is appropriate for a given biomedical application.

However, because of variations in physical-chemical properties of plants due to their geographic location, growing conditions, method of harvesting (extraction), how they are processed after harvest (purification), and other factors, it is necessary to determine the characteristics of the plant material and standardize the material prior to using it in medical applications [11], [19].

Biocompatibility and Biodegradability

Biocompatible materials are necessary when designing materials that will be placed directly into contact with the body's internal environment. Many of the naturally occurring biomaterials can elicit a positive response from the body due to their similarities to or interactions with the body's natural extracellular matrix (ECM) structures [15]. Collagen, which makes up most of the structural components of all types of connective tissue, is one example. Other examples include Silk Fibroin, Chitosan, Alginate, and Cellulose-based materials; these materials have all shown significant promise for use in Tissue Engineering, Wound Management, Drug Delivery and numerous other areas of biomedicine [15], [18].

Biodegradable materials are also common among biomaterials derived from nature. Natural polymers have a variety of different chemical structures that allow them to be degraded by enzymes, water, oxygen, or microorganisms. Degradation can be beneficial in some applications as it provides a way to replace a temporary material with new growing tissue. However, the degradation process should happen at a suitable rate. If the degradation occurs too fast, it will decrease the strength of the material; if the degradation occurs too slowly, it can slow down the process of forming new tissue [18], [19].

While it has been assumed that natural materials are intrinsically biocompatible, such an assumption can not be made about all natural fibers. Residual proteins, chemicals used during extraction, contamination from sources such as insects or dust, impurities from other components of the fiber, endotoxins, or processing aids can affect how a body reacts biologically to a fiber. As a result, the following must be assessed for each individual type of material and **manufacturing process**: Cytotoxicity Inflammatory response Degradation products Sterility In vivo compatibility [20].

Major Natural Fibers for Suture and Catheter Applications

The use of natural fibers and bio-derived polymers has gained momentum in the field of biomedical engineering. These types of polymers offer both biological function and mechanical properties that are desirable in medical applications. Due to the wide variety of chemically different natural fibers and polymers available today, researchers can choose a polymer based upon several factors including; its tensile strength, flexibility, degradation rate, antibacterial properties, ability to stop bleeding (hemostasis), surface modification capabilities and compatibility with living tissues [21]. Many of the most studied natural polymers include; collagen, silk fibroin, chitosan, alginate, cellulose and bacterial cellulose. In addition, there are many studies that evaluate plant-derived fibers (e.g. cotton, flax, hemp) as either a structural component or reinforcing material [22].

Table 2. Major Natural Fibers and Their Applications in Suture and Catheter Systems

Natural Fiber	Key Properties	Suture Application	Catheter Application
Silk fibroin	Strong, flexible, biocompatible	Surgical sutures	Coatings, tissue interfaces
Collagen	Bioactive, biodegradable	Absorbable sutures	Surface coatings
Cellulose	Strong, renewable	Composite sutures	Reinforcement, coatings
Chitosan	Antimicrobial, biodegradable	Antimicrobial sutures	Antimicrobial coatings
Alginate	Hydrophilic, gel-forming	Wound closure systems	Drug-delivery coatings
Keratin	Bioactive, biodegradable	Experimental sutures	Bioactive coatings
Bacterial cellulose	Pure, nanofibrous	Experimental biomaterials	Coatings, anti-biofilm systems

Collagen

Collagen, as a biologically produced biomaterial, is a primary component of the extracellular matrix that plays a key role in supporting tissue structure and mediating cell-to-cell interaction. Of the many forms of collagen available, type I collagen has been identified as a particularly suitable biomaterial for biomedical purposes due to several of its characteristics including: high level of biocompatibility; high level of biodegradability; low levels of immunogenicity; and high levels of cell attachment and tissue regrowth [23]. Collagen can be formed into various forms (such as fibers, films, membranes, hydrogels, sponges, and electrospun forms) allowing for great flexibility when designing medical devices.

Surgical closure was historically achieved using collagen-based products such as catgut-like absorbable sutures; however, current collagen-based products are being studied as potential methods for closing wounds quickly and for regeneration. Since collagen fibers are capable of providing a biomimetic environment that resembles the body's natural extracellular matrix, they are capable of enhancing tissue incorporation into a host organ [23], [24]. Unfortunately, most types of collagens will require either chemical crosslinking or combining with additional materials to increase the mechanical

properties of the collagen and protect the collagen from degradation in the presence of physiological fluids. Both electrospun collagen and electrospun collagen/gelatin fibers are of particular interest due to their nanoscale morphology that can simulate certain features of the extracellular matrix architecture [25]. These properties make collagen a desirable material for absorbable sutures, wound healing systems, interfaces between tissues and possibly functional coatings for medical devices.

Silk Fibroin

Silk fibroin is an organic protein-based fiber that is produced by the silkworm. It is unique due to the combination of mechanical properties (strength and flexibility), slow rate of degradation, and good biocompatibility. The chemical composition of the amino acids in silk fibroin create repetitive patterns that can form crystalline β -sheet structures. These structures are responsible for providing mechanical support and stability [26]. Silk fibroin can be processed into many forms including continuous fibers, films, hydrogels, porous scaffolds, and electrospun nanofibers. These various forms allow for flexibility in meeting specific biomedical needs.

Silk is a traditional suture material, and it will remain useful in the future due to its ability to control the mechanical properties of silk fibroin by manipulating processing, mixing, and cross-linking [26]. Slow degradation may be beneficial if you need the mechanical support for an extended period of time. You can combine silk fibroin with collagen, chitosan, alginate, or synthetic polymers to enhance the mechanical, physical/chemical, or biological properties of the material [27]. However, you must purify the silk fibroin since any remaining sericin or other components could affect the biological response to the material. In terms of catheter applications, silk fibroin is especially useful as a component of coating systems, reinforcing structural elements, and functional biomaterial systems instead of as a traditional catheter material.

Chitosan

Chitosan is a naturally occurring polysaccharide primarily created via the deacetylation of chitin which can be harvested from crustacean shells or other biological resources. Some of Chitosan's most significant biomedical features are: biodegradability, biocompatibility, hemostatic activity, antimicrobial activity, and bioadhesiveness [28]. The protonatable amino groups within the molecule enable Chitosan to form interactions with negatively charged biological surfaces and microbial membranes; therefore enhancing Chitosan's antimicrobial and biological activities.

Chitosan has been identified as having great potential in the area of suture development, due to its ability to assist in the wound closure process by providing both tissue approximation and control of bleeding, infection, and inflammation. There are many ways that chitosan can be processed including; fibers, filaments, coatings, hydrogels, membranes, and composite sutures [29]. Recent studies have focused on using wet spinning, electrospinning, polyelectrolyte complexation, and coating methods to produce chitosan-based sutures that exhibit improved mechanical and biological performances. Due to its antimicrobial and hemostatic capabilities, chitosan is an ideal candidate for development as a multi-functional wound closure material [29]. While pure chitosan fibers have shown promise as suture materials, they often lack the necessary mechanical strength and are sensitive to processing conditions. Therefore, combining chitosan with other materials such as silk fibroin, collagen, cellulose, or synthetic polymers will enhance the structural performance and functional stability of these materials.

Alginate

Alginates are naturally occurring anionic polysaccharides that are extracted mainly from brown seaweeds, but can be produced by microorganisms. Alginates consist mostly of beta-D-mannuronic acid and alpha-L-guluronic acid units that are connected together to form various types of blocks. The primary benefit of alginates is that they will undergo ionic gelation when exposed to divalent cations like calcium. Therefore, alginates may be fabricated into hydrogels, fibers, beads, membranes, and porous materials [22].

Because of alginate's good biocompatibility, biodegradability, water holding capacity, and processability it has been studied extensively in the fields of wound healing, drug delivery, tissue engineering and regenerative medicine [30]. Alginate fibers are capable of absorbing large amounts of fluid and maintaining a moist environment which makes them very attractive for use in wounds. On the other hand, alginate has low mechanical strength and does not maintain itself well in physiological conditions. Thus, alginate cannot be used directly as a component of mechanical devices. For this reason alginate is typically mixed with other materials such as collagen, chitosan, silk fibroin, cellulose, or synthetic polymers to increase both the strength and function of the material [30].

Cellulose and Bacterial Cellulose

Cellulose, the most abundant naturally occurring polymer, is made up of β -(1 $\rightarrow$ 4)-linked glucose molecules arranged in a very structured manner. Plant-based cellulose can be obtained from many different plants such as cotton, wood, flax, hemp and other agricultural products. Because of its large availability, environmental friendliness, mechanical properties, chemical characteristics and capacity to produce both fibrous materials and nanoscale structures, it is considered a promising biomaterial [22], [31].

Bacterial cellulose has many advantages over plant-derived cellulose. It can be produced outside of the cell through biosynthesis, has a higher level of chemical purity than plant cellulose, and has a 3-D nano-fiber network. [31]. In addition to being highly hydrated with excellent water-holding capabilities, it also exhibits good mechanical properties as well as a great degree of biocompatibility. Plant cellulose requires significant processing to remove both lignin and hemi-cellulose before it can be utilized in similar ways as bacterial cellulose. The unique multi-dimensional fibrous nature of bacterial cellulose makes it suitable for numerous application areas including: tissue engineering; wound dressings; drug delivery systems; etc. [32].

Cellulose and bacterial cellulose can be utilized in suture and catheter applications as fibrous scaffolds, reinforcing components, coatings, membranes, and platforms for incorporation of antimicrobial or therapeutic agents. However, limited intrinsic biodegradation within the human body and difficulty in obtaining the mechanical properties needed for some implantable applications are still significant issues [31], [32] .

Cotton

Cotton is a natural fiber that comes from the seeds of various types of *Gossypium* plants. It is primarily made up of cellulose and has many properties which make it very suitable for use in health care textiles. Some of these include; high cellulose content, porosity, surface area, flexibility, and the ability to absorb fluids. Due to these attributes, cotton can be used to develop medical textiles and wound care products [22] Cotton-based materials are being researched as potential alternatives to synthetic materials for wound dressings, drug delivery systems, tissue engineering, and surgical applications. Modifications to cotton such as chemical oxidation or functionalization can enhance its fluid absorption, hemostatic behavior, and overall biological performance. Although cotton is not typically viewed as an optimal primary material for modern implantable sutures, its long history of being used in medical applications and the possibility to modify its cellulose structure create opportunities for developing functional fibrous biomaterials [33] .

Flax

Flax (*Linum usitatissimum*), a bast fiber with a large amount of cellulose, offers good physical and mechanical characteristics. To evaluate the feasibility of using flax as a biomaterial, purified and knitted flax structures were developed to be used in surgery [34] . Studies showed that when properly purified, flax-based materials could provide cell compatibility and good response to tissues. One of the main factors to consider when evaluating flax-based materials for use as implants is the removal of all endotoxins and other contaminants that come from the plant itself. Thus, before flax can be used as an implantable biomaterial, it must undergo purification and quality control. In addition to being strong for its weight and coming from a renewable source, flax is a good candidate to reinforce composite biomaterials made from natural fibers [35] .

Hemp

Hemp (*Cannabis sativa* L.) is a renewable, bast-fiber source that contains cellulose along with hemicelluloses, lignins, and pectins. Hemp fibers have relatively high strengths and low densities; therefore, they are being researched as environmentally friendly reinforcing agents [22] . The mechanical properties of hemp fibers provide potential benefits when incorporated into composite biomedical devices, such as those that require higher stiffnesses and/or longer service lives. Although untreated hemp cannot be used as a direct replacement for existing medical-grade biomaterials, there are several steps that must occur prior to its use in medical implants including cleaning, surface treatments, evaluations of biocompatibility, and sterilizations. Therefore, the current application of hemp-based products in medicine will likely occur through modification or the development of composites using hemp [36] .

Other Emerging Natural Fibers

There are several additional examples of natural protein and polysaccharide fibers that could potentially serve as biomaterials. For example, keratin is extracted from biological sources such as hair, wool, feathers, etc., that contain large amounts of keratin. Keratin is rich in cystine and disulfide linkages and has been shown to have biological activities useful in wound healing, tissue engineering, and drug delivery [22] . Keratin can be processed into fibers, films, hydrogels, and scaffolds, and may create bioactive environments for cellular interaction. Gelatin, which is produced by hydrolysis of collagen, is a biomaterial that is also versatile. Gelatin can be processed into electrospun fibers or added to composite fibers due to its biocompatibility and similarity to proteins found in the extracellular matrix. Hyaluronic acid, a naturally-occurring glycosaminoglycan found in the extracellular matrix, can also be formed into nanofiber structures, and exhibits high levels of hydration and biological activity [23] . When used with proper reinforcing or cross-linking strategies, these biomaterials may enhance the performance of next generation sutures and catheter coatings.

Natural Fibers in Suture Applications

Sutures are one of the most widely used medical devices and continue to be essential for closing surgical wounds. The choice of suture material directly affects how well the wound edges come together, how strong the wound will be, what kind of inflammatory reaction occurs, what the probability of contracting an infection is, and how quickly the wound will heal. For centuries prior to the advent of modern synthetic polymers, natural fibers (e.g., silk, catgut, cotton, etc.) were commonly utilized in surgery. Today, researchers are again turning their attention to natural fibers since many natural polymer-based materials (e.g., collagen, silk fibroin, chitosan, etc.) offer both mechanical strength and biological function, which may be difficult to achieve using only standard synthetic polymers [37], [38]

Requirements of an Ideal Suture Material

The optimal suture will have sufficient strength to provide support for a healing wound as long as mechanical support is needed, then degrade or be removed from the site of the wound with little or no damage to the surrounding tissues. There are many other qualities that make up the "ideal" suture such as flexibility, elasticity, predictability in degrading, biocompatibility, minimal reactivity with tissues [37], [39] . and ease of passage through tissues. The suture should also allow the clinician to pass through the tissues with very little trauma to the surrounding tissues. In addition, the suture should not promote excessive bacterial growth or infection. The required physical characteristics of a suture will vary based on the location of the wound and how fast it heals. Tissues which heal very quickly can be supported for a short

period of time using absorbable sutures. However, tissues such as ligaments and tendons which are under significant mechanical stress will need to retain their strength for an extended period of time [40]. Therefore, a desirable absorbable suture would lose its strength at a controlled rate throughout the process of tissue remodeling, while maintaining sufficient strength during this time frame. Conversely, non-absorbable sutures would remain structurally intact for long periods of time and result in relatively low levels of chronic inflammatory response. In addition to considering mechanical properties of sutures, modern suture designers are now also considering antimicrobial properties, drug delivery systems, tissue regeneration capabilities, and controlled interaction with the wound site [41] .

Historical Use of Natural Fibers in Sutures

The employment of naturally derived substances for wound closure occurred long before the development of modern biomaterials technology. In early surgical procedures, physicians utilized naturally occurring components such as plant fibers, animal tissues, silk, linen, etc. Catgut, developed from animal intestinal tissue containing high levels of collagen, was one of the first well-known absorbable sutures, whereas silk became a significant non-absorbable suture due to its flexibility, handling capabilities, and knot security [42] .

Silk is a material with a long history of use in clinical practice, and even though there are many other types of synthetic materials available today, it still plays a role in some specific types of surgeries [43] . The use of natural sutures was an important step forward in the evolution of materials used in surgery; it showed that biological fibers could function as a structural support system while interacting with living tissue. However, because of differences in the composition, rate of degradation, response to tissue, and risk of infection associated with natural sutures, researchers developed synthetic polymers that would allow for greater predictability [37] .

Natural Fiber-Based Suture Materials

The research community has studied many different types of naturally occurring fibers and biopolymers to develop new suture materials. Of these materials, silk fibroin is especially relevant due to the fact that it possesses several beneficial properties including: high tensile strength; flexibility; toughness; and relatively slow degradation rates. Additionally, silk can be manufactured into either monofilament or multifilament structures and can be modified to contain antimicrobial or therapeutic compounds [42], [43] . Given the long-standing use of silk as a surgical suture material, there is a good foundation to continue researching advanced suture materials derived from silk.

Collagen, a major component of connective tissue, is a valuable natural material that has many properties well suited for repairing damaged tissues. Collagen-based fibers are capable of supporting the growth and development of cells, as well as the creation of an extracellular matrix. When the collagen degrades, this will be done via enzyme-mediated processes [44] . To enhance the mechanical strength and to regulate the degradation process, collagen is typically crosslinked or blended.

Chitosan is an ideal material to use in multi-functional sutures. Chitosan offers many advantages including being biodegradable, biocompatible, antimicrobial, hemostatic, and anti-inflammatory [45] . Recent research on chitosan sutures includes wet spun, electrospun, coated, and composite types of sutures. Incorporating chitosan into a suture structure can offer more biological functions than just mechanical support. A recent study examined wet spinning, melt spinning, electrospinning, interfacial polyelectrolyte complexation, and coating as potential methods to produce chitosan-based sutures [45] .

Other naturally occurring polymers such as alginate, gelatin, cellulose, keratin, and hyaluronic acid have also been used in fiber-based wound healing applications and potentially could be developed into new types of sutures [38], [46] . It is possible to combine these materials together or with synthetic polymers to enhance each other's deficiencies. A composite suture made up of both natural and synthetic components can utilize the biological functions of the natural polymer, but will benefit from the enhanced mechanical properties (tensile) and uniform manufacturing characteristics provided by the synthetic component [39].

Mechanical Strength and Flexibility

A key criterion that determines whether or not a fiber can be used in suture applications is how well it performs mechanically. When a wound is closed, the suture is subjected to various forms of tensile forces caused by tissue movement, swelling, muscular contractions and external mechanical stresses. Therefore, the suture must have sufficient tensile strength, and it must continue to provide adequate support throughout the essential phases of the healing process [39] .

Silk is especially appealing due to the fact that its fibroin structure has an excellent balance of tensile strength, toughness, flexibility, and controlled degradation [43], [44] . In addition, the mechanical properties of silk can be adjusted by changing the size of the fibers, how they are spun, their molecular arrangement, braiding, and after-spinning treatment. Collagen based sutures offer potential biological benefits, however, most collagen based sutures need to be cross linked or combined with other materials to improve their mechanical stability [45] .

The biological properties of chitosan fibers make them attractive candidates for sutures. However, compared to commercial synthetic suture materials, chitosan fibers may have poorer mechanical characteristics. There are several ways to enhance the mechanical properties of chitosan fibers including crosslinking, blending with silk fibroin or other polymeric systems, and controlling the spinning process to optimize mechanical performance [46] . Natural fibers are sensitive to moisture due to the effect of hydration on intermolecular interactions that can ultimately lead to a decrease in mechanical strength. Natural biological sources can produce variations in fiber diameter, crystallinity, molecular structure and defects that will affect mechanical performance. To achieve reproducibility of mechanical performance, it is necessary to control these variables [43].

Biodegradation and Tissue Response

The rate at which a suture degrades should match the biological needs of the area that is being repaired. Sutures made from natural products may degrade through enzymes, water (hydrolysis), oxygen (oxidation), or other biologically mediated means. Materials derived from collagen are susceptible to degradation by enzymes, whereas materials derived from silk generally degrade at a slower pace due to their crystalline beta-sheet structures [44], [45] .

Suture material's chemistry, surface morphology, degradation products, structure and implantation site will determine what type of reaction the suture material has to the body's tissues [47]. Natural suture materials may have reactions to foreign bodies. Studies in the past showed that there was a large amount of tissue reaction to some natural sutures, especially silk and catgut; however, the level of reaction depends on the material properties and tissue environment [48] . Recent studies compare the levels of bacterial attachment and tissue reaction caused by different suture materials. These studies show that monofilament synthetic materials can cause less tissue reaction than natural multifilament suture materials [48] .

As such, controlled degradation provides a significant benefit for absorbable natural sutures. As new tissue forms, the mechanical properties of a collagen or protein based suture can slowly degrade, therefore reducing the likelihood that the suture will have to be removed. It is necessary that the degradation rate of the suture is predictable enough so as to avoid premature loss of strength which could result in wound dehiscence and that the degradation rate does not take so long that it causes prolonged inflammation or foreign body reactions [45] .

Antimicrobial and Wound-Healing Properties

The occurrence of post-operative infection is a significant complication related to both surgical wounds and the use of implanted sutures. Since sutures are placed directly into contact with the damaged tissue, they can potentially act as a base upon which microbes may adhere and form biofilms [49] . Thus, biologically active natural fibers offer a promising avenue to create multi-functional sutures.

In particular, chitosan is especially interesting as it contains positive charge amino groups that are capable of interacting with negative charge microbial cell membranes and therefore contribute to its anti-microbial properties [46], [50] . Chitosan has also been shown to promote blood clotting (hemostasis) and influence wound healing processes. Studies using animals to investigate wounds have demonstrated that after being treated with chitosan there was an increased early inflammatory response and increased collagen production which indicates possible advantages in terms of tissue repair [51] .

Silk fibroin by itself is usually thought to have biocompatibility and biodegradability, but because it has minimal natural antibiotic properties, it is often necessary to use additional antibiotic materials or coating if the goal is to prevent infections [44] . There have been studies that looked into combining silk fibroin with chitosan, as well as several other types of antibiotic components, so that fibrous materials could be developed that were more resistant to colonizing microbes [51].

Natural Fiber-Based Sutures versus Synthetic Sutures

The use of synthetic suture material has significantly replaced the use of numerous natural suture materials due to the fact that they offer greater control over their chemical structure, physical characteristics, size/diameter, degradation profiles, and manufacturing methods. Examples of synthetic suture materials include polypropylene, nylon, polyglycolic acid, polydioxanone, and similar polymer-based materials which provide predictable mechanical characteristics and degradation patterns [37], [41] . Synthetic monofilament suture materials may also demonstrate less bacterial adherence and less tissue reaction than other types of natural multifilament suture materials [51] .

However, natural fibers have some unique benefits compared with traditional man-made synthetic polymers. Silk, collagen and chitosan can provide both structural integrity and biological function. Chitosan is also naturally anti-bacterial and promotes blood clotting [40], [50] . Natural polymers are capable of providing chemical signals which can promote interaction between cells and aid in wound healing. On the other hand, natural polymers do have several disadvantages including inconsistency, possible variability in degradation rate, susceptibility to water damage, relatively low mechanical strength for certain types of natural polymers, and difficulty with standardizing and sterilizing them [38].

Table 3. Comparison of Natural Fiber-Based and Conventional Synthetic Suture/Catheter Materials

Parameter	Natural Fiber-Based Materials	Conventional Synthetic Materials
Biocompatibility	Generally high	Generally high, material-dependent
Biodegradability	Often biodegradable	Variable; many are slowly degradable/non-degradable
Mechanical strength	Moderate to high; variable	More predictable and tunable
Bioactivity	Can support tissue interaction	Usually relatively inert

Antimicrobial activity	Possible with chitosan or functionalization	Usually requires modification/coating
Sustainability	Renewable and potentially eco-friendly	Mostly petroleum-derived
Batch consistency	Can be variable	Generally high
Clinical maturity	Limited for many emerging materials	Well established

Natural Fibers in Catheter Applications

Catheterization is an essential component of many medical procedures including but not limited to; urinary drainage, vascular access, delivery of drugs/fluids, managing fluid status, and monitoring physiological functions. While catheters are critical to clinical practice, conventional catheter material (silicone, polyurethane, PVC, latex, polyethylene) can promote microbial attachment, create a site for biofilm growth, result in encrustation/thrombosis/inflammation, and cause mechanical problems over time [52]. Therefore, there has been an increased interest in developing biomaterial based catheter systems that offer superior biocompatibility/antimicrobial properties/antifouling behaviors/controlled degradation. Silk fibroin, chitosan, collagen, and bacterial cellulose are all examples of natural fibers/polymers that possess numerous advantageous attributes for catheter development whether used as structural elements, components of composite structures, or as coating materials [53].

Requirements of an Ideal Catheter Material

An optimal material for use in a catheter will exhibit a proper combination of mechanical strength, flexibility, dimensional stability, surface functions, and biological compatibility. Mechanical strength is needed to resist being damaged during insertion, manipulation, bending, compression, and twisting forces without failing or permanently deforming. Additionally, a sufficient amount of flexibility is required to enable the catheter to conform to anatomical structures and reduce potential damage to surrounding tissues [52].

The catheter's surface needs to be smooth, slippery, and hydrophilic enough to decrease the amount of friction when it is inserted or removed. In addition, if the catheter will be used for a long period of time, then the catheter's ability to resist bacteria, biofilms, protein deposits, and mineral build-up is very important. Additionally, the catheter's material must also exhibit a low level of toxicity, minimal inflammatory response, appropriate blood compatibility for those used in blood-contacting applications, and predictable interactions with adjacent tissues [53]. Lastly, since catheters may come into contact with body fluids, disinfectants, medications, and sterilization methods, they must also be chemically stable and capable of being sterilized. Therefore, a ideal catheter would have both the consistency in manufacturing of traditional polymers and the biological function of advanced biomaterials.

Role of Natural Fibers in Catheter Development

Natural fibers can be used as structural fibers, reinforcing components, surface coatings, hydrogels, or drug-containing matrices to support the development of catheters. The main advantage of these materials is that they can combine mechanical performance and biological functionality. For instance, silk fibroin has high mechanical properties and can biodegrade at a controlled rate, which makes it an ideal material for tubular biomedical structures [43].

Chitosan has been shown to offer added value due to its biodegradability, biocompatibility, cationic nature, and inherent antimicrobial properties. The aforementioned attributes of chitosan provide it the ability to serve as an antimicrobial/anti-biofilm coating for standard catheter substrates [54], [55]. Collagen offers biological characteristics similar to those of extracellular matrices, allowing for the potential of cellular interactions. Bacterial cellulose has a well-developed, interconnected nanofibrillar structure; is able to hold large amounts of water; and exhibits good mechanical strength [56]. Therefore, natural materials have the capability to provide functions that are typically not achievable using conventional polymers alone. Additionally, these materials may be modified through blending, cross-linking, chemically modifying them, incorporating nanoparticles, or combining them with synthetic polymers [8].

Natural Fiber-Based Catheter Systems

Natural fiber-based catheter systems are typically categorized as either natural polymer-coated conventional catheters, natural polymer composite catheters, and/or predominantly/fully natural polymer tubular structures. Currently, surface modification of conventional catheters is among the best approaches for using natural fibers as a material for catheters. The substrate provides mechanical support, and the natural coating offers biological function.

Chitosan-coated urinary catheters have been the subject of extensive research. Chitosan has the ability to be deposited on a catheter's surface, which prevents microbes from attaching to the catheter and developing biofilms. Rubini et al., for example, showed that chitosan obtained from marine crab shells and used to coat urinary catheters significantly decreased both mono-species and mixed-species biofilms composed of *Staphylococcus epidermidis* and *Candida albicans* [54]. In addition to reducing biofilms, the chitosan treatment affected microbial virulence-related traits. These findings suggest that natural polymers could have other applications beyond just altering the physical properties of a catheter's surface.

Another study evaluated chitosan's ability to inhibit biofilm formation on silicone urinary catheters. This study found that chitosan has the potential to decrease both bacterial regrowth and biofilm development [55]. These results are significant

since although silicone is a commonly used material for urinary catheters it can still allow for the growth of microorganisms when utilized over an extended period of time.

Silk fibroin-based catheter systems are a more sophisticated method for developing catheters. In this case, the catheter is made from a naturally occurring protein. A catheter created from silk fibroin was developed via infusion molding by Xie et al., and they also added microscopic papillae to the internal surface of the catheter that were based on the design of the lotus leaf [57]. The micro-patterned silk catheter had the ability to prevent adherence to the catheter from *E. coli* and *S. aureus*. Additionally, the micro-structure stayed intact for long periods of time under aqueous environments, while the silk demonstrated acceptable mechanical and biological characteristics [57]. This shows that it is possible to combine natural-polymer chemistry with bio-mimetic surface engineering.

Chitosan/silk fibroin composite systems offer an additional key strategy. When combining chitosan with silk fibroin, you can overcome some of the disadvantages of using either polymer alone. The addition of silk fibroin enhances both the mechanical properties (strength) and physical integrity (structural stability) of the composite system, while the addition of chitosan provides antimicrobial action and biodegradability [8]. These composites can be prepared in various forms such as films, fibers, membranes, hydrogels, and coatings, so they can potentially be applied to catheter surfaces or tubular structures.

Bacterial cellulose-based systems are also becoming increasingly popular. Bacterial cellulose is composed of a 3-D network of cellulose nanofibers, which has many desirable properties including: high water absorption, flexible nature and good mechanical properties [56]. Furthermore, the open pore structure of bacterial cellulose provides opportunities to incorporate other biological materials and drugs into the system. For example, researchers have developed chitosan doped bacterial cellulose hydrogels that have shown antimicrobial activity and have been evaluated as a possible material to treat urinary tract infections [58]. While currently no commercially available bacterial cellulose-based catheters exist, they provide evidence of the potential that natural fibers offer as base materials for new catheter designs.

The use of naturally occurring polymers from marine organisms is a relatively new approach. A naturally occurring polymer from cyanobacteria has been shown to have a wide range of anti-adhesive properties toward numerous types of urinary tract bacteria, such as *Escherichia coli* (*E. coli*), *Proteus mirabilis*, *Klebsiella pneumoniae*, methicillin resistant *Staphylococcus aureus* (MRSA), and *Candida albicans* [59]. Additionally, this coating was able to decrease both biofilm development and crystal deposition, which means that natural polymers can potentially help to prevent both microbiological and physical/chemical reasons for catheter malfunctions.

Mechanical Strength and Flexibility

Mechanical performance is essential to catheter function because they will be subjected to the force of insertion, bending, compression, twisting, and repeated use. If the mechanical performance is poor, then there could potentially be problems with cracking, collapse of the lumen, deformation, or even device failure. On the other hand, if mechanical performance is too strong (stiff), it could lead to increased damage to surrounding tissues and increased discomfort for patients [54], [55].

The reason silk fibroin is so popular as a material for catheters is due to its mechanical strength and flexibility provided by the β -sheet rich nature of the molecular structure of the protein. The ability to process silk fibroin in many ways such as; fibers, films, tubes, hydrogels, and porous structures allows the mechanical properties of the catheter to be altered depending upon what the catheter will be used for [43]. In recent catheter studies using silk fibroin, the researchers found that by altering the crystalline β -sheet structure, they were able to enhance the swelling resistance, strength and flexibility of the catheter [57].

In addition to providing a mechanically integrated nanofibrous network, bacterial cellulose can be strengthened by creating a composite [56]. Since natural polymers often change their mechanical properties upon hydration, there are several methods such as cross-linking, mixing with synthetic polymers, or incorporating strengthening elements into the polymer matrix that can enhance the mechanical performance of natural polymers so that they have the reliability needed for catheter applications [8].

Antimicrobial Properties and Biofilm Prevention

Biofilms represent a major concern when using indwelling catheters. After initially attaching to the catheter surface, microorganisms develop extracellular polymeric substances that stabilize their communities. Once formed, mature biofilms are typically very resistant to removal and can lead to repeated or long-term catheter-related infections [53].

Chitosan shows great promise as a surface coating material due to the ability of its positively-charged amino group to bind to the negatively-charged surface of bacteria, which disrupts the cell membrane and inhibits bacterial growth [54], [55]. Surfaces coated with chitosan show significant reduction in biofilm formation for many types of microorganisms, such as *S. epidermidis*, *S. aureus*, *K. pneumoniae*, *P. aeruginosa*, and *C. albicans* [60].

Specifically, natural polymers can also provide an alternative means to inhibit biofilm development on medical devices by providing a mechanism that prevents attachment of microorganisms as opposed to directly killing microorganisms. The cyanobacterial polymer coating created by Costa et al. showed 68-95% anti-adhesive activity towards various urinary tract infection-producing bacteria and was able to reduce the amount of biofilm produced under biofilm-forming conditions [59]. In addition, it was able to inhibit crystalline encrustation which provides evidence for the development of multi-functional catheter coatings.

Silk fibroin has also been modified to create micro- and nanoscale surface topography which will prevent bacteria from adhering to it. The lotus-leaf inspired micropapillary silk catheter created by Xie et al. was shown to repel *E. coli* and *S. aureus*, while still having desirable biological characteristics [57]. Therefore, developing next-generation catheters with

both the inherent antimicrobial properties of silk fibroin and the physical anti-adherence characteristics created through its surface structure may be a very effective approach.

Drug-Eluting Natural Fiber-Based Catheters

Natural polymers are another type of matrix that may be used to deliver drugs locally to catheter surfaces. Because they contain functional groups, have a porous structure, and are able to form hydrogels and films, they allow for the inclusion of therapeutic agents such as antimicrobials, anti-inflammatories, etc. For instance, collagen has been studied as a biomaterial for controlled drug delivery due to the fact that its structural properties enable the incorporation of biologically active molecules; furthermore, collagen can be chemically crosslinked to control the rate of molecule release [61].

Silk fibroin is an excellent candidate for developing drug delivery systems due to its controllable degradation properties, mechanical stability, and ability to load/embed/retain active compounds [54]. A drug-eluting natural polymer coating may offer long-term localized antimicrobial action with diminished systemic absorption. On the other hand, the optimization of drug incorporation, elution rate, adhesion of the coating to the catheter surface, sterilization procedures and preservation of efficacy over the duration of catheterization will need to be carefully considered.

Biodegradable and Bioresorbable Catheter Systems

The use of biodegradable natural materials provides potential for temporary catheter systems as well as transient functional coatings. Silk fibroin has been shown to have a controlled biodegradation rate based on its ability to alter its degradation properties by changing its crystallinity, crosslinking, and processing [43]. Similarly, both chitosan and bacterial cellulose can be integrated into biodegradable composite materials.

The controlled degradation process of some biomedical materials may allow devices to be temporarily released from the body rather than completely removed when they are used in certain types of application. Also, the rate at which biodegradation occurs should always match how long a particular catheter will be implanted into a patient's body. If the material degrades too quickly, the device may lose its ability to perform its function before it is scheduled to be removed. On the other hand, if the material degrades too slowly, then the patient may not receive the full benefit of using a biodegradable device [8], [58].

Natural Fiber-Based Catheters versus Conventional Catheters

Conventional silicone, polyurethane, PVC, and latex catheters provide well-established manufacturing methods, predictable size, good mechanical strength, and a large body of clinical experience. On the other hand, the catheter surface can still be prone to bacterial attachment, development of biofilms, and formation of scales [53]. In addition to these benefits, natural fiber-based systems have several other advantages: they are biodegradable, inherently biologically active, can incorporate anti-microbial functions, can allow for incorporation of drugs into the catheter, and their surface properties can be adjusted [8].

However, natural materials have limitations such as variability of raw materials, moisture sensitivity, sterilization, mechanical stability, reproducibility, and lack of long term clinical studies. Thus, it appears that the use of hybrid catheter systems, which combine conventional structural polymer with natural fiber-based functional coating is a more realistic alternative to totally replacing conventional catheter materials.

Manufacturing and Processing Technologies

Manufacturing processes significantly affect the mechanical, structural, biological and surface properties of natural fiber based biomaterials. The process should maintain all the benefits of the natural fiber while also allowing for reproducibility, dimensional accuracy, sterilization and specific mechanical performance required for the product application (suture/catheter). Therefore, extraction, fiber formation, textile processing, electrospinning, coating, composite fabrication and other advanced manufacturing techniques may be chosen based on the intended use of the biomaterial in suture/catheter applications.

Extraction and Purification of Natural Fibers

The first step in transforming biological source material into biomedical-grade fibers is through extraction and purification. Typically, plant-based fibers are subjected to mechanical separation; then, they may be processed using alkaline, acid, bleaching, enzyme, or a combination of these processes to eliminate lignin, hemicelluloses, waxes, proteins, and other impurities [62]. For example, animal-derived fibers (e.g., silk) will require elimination of sericin and other non-fibroin components while collagen will need to be isolated and purified from biological tissues. It is essential that the extraction conditions are optimized as excessive chemical treatment can result in reduction of molecular weight, damage to the fiber structure and/or impairment of the mechanical or biological characteristics [62].

Spinning and Fiber Formation

Spinning is the process that allows the conversion of refined biological materials into continuous fibers that are characterized by controlled diameter, orientation and mechanical properties. A variety of spinning processes including; wet spinning, dry spinning, melt spinning, microfluidic spinning and solution based processes have been studied with respect to spinning of natural polymers (silk, chitosan, cellulose and collagen) [63]. The ability to control both fiber alignment and molecular orientation during spinning can significantly enhance the fiber's tensile strength and toughness. Silk Fibroin has shown itself to be a good candidate for spinning as the molecular structure of Silk Fibroin can be altered through processing to create bio-fibers with high strength and flexibility [63].

Braiding and Weaving

The process of braiding and weaving individual fibers creates organized textile structures. In particular, both processes have significant relevance to surgical sutures due to the ability of each to provide control over tensile strength, flexibility, knot security, surface texture, and handling characteristics. Braided structures can distribute load among many individual filaments and therefore may have greater flexibility than a single monofilament structure. Similarly, weaving can create porous structures with controlled geometry. However, high levels of friction between the individual fibers or variation in fiber size can impact mechanical performance and surface properties.

Electrospinning

Electrospinning is a significant process for forming micro to nano scale fiber structures from natural polymers. During this process, a polymer solution is exposed to a high electrical potential, which forms a charged liquid stream that stretches into a fine fiber and deposits onto a collector. The size and shape of the fibers are determined by several factors, including the polymer concentration, viscosity, electrical conductivity, characteristics of the solvent used, the electrical potential applied, the rate of flow of the solution, the distance between the needle and the collector, the temperature, and the relative humidity [64] .

Natural polymers such as collagen, gelatin, chitosan, alginate, cellulose derivatives, silk fibroin and keratin are being developed through electrospinning into fibrous structures that provide high surface area and desirable biological properties [64] . Electrospun materials are very good for functional coatings, drug delivery, tissue-interface applications and biomimetic structures; however, many of the natural polymers used for electrospinning are difficult to process due to poor spinnability and will need to be blended or cross-linked in order to produce fibers with sufficient mechanical stability.

Coating Technologies

Coating technology allows us to functionally modify a pre-existing fiber or catheter while maintaining the bulk structural properties. A variety of coating techniques (dip coating, spray coating, layer by layer assembly, plasma-assisted deposition and solution coating) can create surfaces that have antimicrobial activity, provide lubrication, increase hydrophilicity or release drugs. Quality indicators include the thickness, uniformity, adherence, and resistance to being washed off or exposed to physiological fluids of the coating.

Composite Fabrication

The fabrication of composites incorporates natural fibers with other materials (polymers) that are used in conjunction with them so that the disadvantages of each component can be eliminated. Natural fibers can be added to polymers via many different methods such as blending, impregnation, molding, and solution processing. For instance, composite materials made from cellulose- and silk-based fibers, films, hydrogels, etc., can be engineered to have a wide variety of tunable mechanical and biological characteristics [65] . Composite manufacturing is especially beneficial when there is a need to reinforce natural fibers or provide them with enhanced dimensional stability.

Advanced Manufacturing and 3D Printing

Natural polymers may be fabricated into complex geometries via advanced manufacturing techniques, such as additive manufacturing/3D printing, which cannot be achieved with traditional textile processing methods. There are several ways to process natural polymers into 3D structures: extrusion-based printing, stereolithography compatible formulations, inkjet printing, and biofabrication approaches [65] . While these technologies provide control over many parameters of the product being produced (e.g., porosity, internal architecture, size, patient-specific geometry), there remain significant issues related to natural polymer systems, including printability, mechanical properties, drying/crosslinking, and post-processing stability.

Sterilization and Packaging Considerations

Sterilization of bio-medical natural fiber products is critical to ensuring microbial safety while maintaining the product's mechanical and biological properties. Methods used for sterilization include steam, ethylene oxide, gamma irradiation, electron-beam irradiation, and some chemicals. Response of natural materials to sterilization varies widely; sterilization can affect the molecular structure, crystalline content, mechanical properties, and degradation rate of silk fibroin [65] . Therefore, the sterilization method must be verified for every formulation and manufacturing technique.

The packaging used for natural fibers should keep the fibers free of moisture, oxygen, dirt/contamination, and physical harm. Additionally, the packaging should maintain the sterility of the fibers until they are consumed within their specified time frame. Natural fibers are typically hygroscopic and as such require moisture-barrier packaging. Changes in moisture level can alter the mechanical properties (i.e. tensile strength, flexural modulus) of the natural fibers, along with their rate of degradation. Therefore, it would be advantageous to develop the natural-fiber suture/catheter manufacturing processes, sterilization processes, and packaging processes as part of a single continuous process.



Figure 2. Manufacturing Strategies for Natural Fiber-Based Biomedical Devices

Challenges and Limitations

Biomedical applications of natural fibers have the potential to provide biocompatible, renewable materials with tunable degradation rates; however, there are many challenges that limit the use of these materials as sutures and catheters. The major limitations include material heterogeneity, environmental sensitivities, manufacturing complexities, sterilization effects on properties, and difficulties in predicting degradation. Each of these limitations may impact device performance, reproducibility, shelf-life, and clinical reliability. Thus, to successfully develop natural fiber-based biomedical products and gain regulatory approval, it will be necessary to establish standard criteria for raw material selection, control processes, validate sterilization methods, and develop product-specific performance tests. It will also be critical to consider how natural fiber-based devices will perform under mechanical load and fluid exposure conditions.

Batch-to-Batch Variability

As a result of differences in biological origin, such as species, growth environment, harvest time, extraction process and purification methods; natural fibers have varying compositions, fiber diameters, degrees of crystallinity, molecular weights, moisture contents and mechanical properties. This can lead to differences in tensile strength, degradability, and surface characteristics among various lots of natural fibers. In order to enhance reproducibility for consistency in clinical performance, it is essential that natural fiber sources be standardized, their compositions be characterized and quality standards be established [22].

Mechanical Strength and Durability

Natural fibers can be strong and tough; however, they often lack the required mechanical properties (strength and/or toughness) needed for use as long term biomedical device materials. Also, after hydration and processing, the mechanical properties of these types of fibers can change. The mechanical properties of natural fibers are greatly affected by fiber orientation, defect density, interfacial bonding quality, processing conditions (temperature, pressure, etc.), and environmental exposures [63]. If natural fiber-based sutures do not have sufficient tensile strength or adequate fatigue resistance, then the ability to maintain knot security and support wounds will be compromised. In addition, when natural fiber-based catheters are used, it is necessary to provide adequate flexibility, kink resistance, and dimensional stability.

Moisture Sensitivity and Stability

Many natural fibers are hydrophilic, meaning that they easily take up environmental or physiological moisture. The taking-up of moisture can result in swelling, plasticizing, decreased stiffness, dimensional changes, and accelerated degradation of properties [66]. Therefore, moisture-barrier packaging, controlled humidity in storage areas, protective coatings, and proper conditioning will allow for maintaining performance throughout both storage and usage periods when exposed to variable environmental conditions. These factors are critical to preserving performance characteristics of moisture-sensitive fibers over all types of storage conditions.

Processing and Manufacturing Challenges

The process of extracting natural fibers includes several stages; i.e., extraction, purification, drying, modifying and then forming. All these stages affect the molecular structure of the fiber as well as its overall performance. Therefore, scaling-up the laboratory-scale processes into large scale industrial ones is not straightforward as many of the laboratory-scale process conditions do not necessarily apply to the industrial scale production. In order to achieve reproducibility in terms of dimensions, composition, porosity, mechanical properties, etc., there is a need for standardized process parameters as well as in-process control mechanisms [67]. Compatibility among various pieces of equipment adds another layer of complexity.

Sterilization Challenges

Sterilization of natural biomaterials presents a challenge due to potential changes in the biomaterial's molecular structure and biological performance that may occur from exposure to heat, radiation, chemical agents or plasma. Research has shown that sterilization of silk-based biomaterials can change biomaterial stiffness, molecular properties, and degradation rate [68], [69]. Therefore, sterilization methods must be chosen and validated so as not to damage the mechanical

properties of the biomaterial, its biocompatibility, or the planned degradation of the biomaterial. Additionally, the compatibility of the sterilized biomaterial with the packaging material must be determined.

Control of Biodegradation

Biodegradation is an advantage when a short term use of a device is needed; however, the uncontrolled biodegradation may lead to early loss of strength or unpredictable device life. Biodegradation depends on fiber composition, crystallinity, crosslinking, processing, implantation site, and enzyme activity [7]. Therefore, to achieve predictable biodegradation, we need to design materials, test degradation, and relate the results to how the material will behave in-vivo. We can also use kinetic models to help us predict the clinical life of the device.

Recent Advances and Emerging Trends

Biomedical devices using natural fibers have evolved recently from being passive structural components to multi-functional units incorporating structural integrity, anti-microbial capabilities, degradation control, sensing, and drug release. To address shortcomings and enhance the efficacy of these devices, hybridizations with synthetic polymers, nano-scale engineering of fibers, response to external stimuli, and addition of bio-active molecules are being investigated [14].

Natural Fiber–Synthetic Polymer Composites

Recent progress has led to an increasing number of natural fiber-based biomedical devices becoming active multi-functional systems rather than passive structural materials, providing mechanical support, antimicrobial activity, controlled degradation, sensing and drug delivery capabilities. Synthetic polymer hybridisation, nanostructured fiber engineering, stimulus response, and bio-active functionalization are all being used as strategies to enhance clinical efficacy while addressing some of the current limitations [14] [18].

Nanofiber-Based Biomedical Devices

Nanofibers based devices offer large surface areas, highly interconnected pores and flexible architecture which makes them highly desirable for application in biomedical interfaces and local delivery. Electrospinning allows us to convert natural polymers like collagen, chitosan, gelatin and silk derived materials into nano-scale fibers; whereas hybridization can enhance the mechanical properties [70]. The most recent advances have focused on controlling the fiber diameter, alignment of the fibers, pores size/shape, and the incorporation of drugs. All these properties will help develop wound contacting materials, regenerative scaffolds, anti-microbial surfaces and advanced drug eluting bio-medical platforms.

Smart and Stimuli-Responsive Materials

As well as the development of smart/stimuli responsive materials that are able to react to either internal or external stimuli (i.e. pH, temperature, enzyme, light, magnetic field, redox) many types of bio-based polymers (chitosan, etc.) have the ability to swell/contract/change their permeability upon stimulation [71], [72]. The use of these properties within a catheter/suture system will allow for environment-sensitive drug release, adaptive interface, and responsive anti-microbial activity. These systems will be able to deliver targeted therapy.

Antimicrobial Natural Fiber Systems

Natural systems that exhibit antimicrobial activity have increasingly been combining the inherent biological properties of these systems with surface modification or the incorporation of antimicrobial agents. Chitosan is especially promising due to its positive charge which allows it to damage microbial cell membranes, while the fiber provides a large surface area for attaching antibiotics, peptides, nanoparticles, or plant extracts [72]. The goal of today's research is to develop long-term antimicrobial activity while limiting toxicity to cells and decreasing exposure to antibiotics. These systems would be useful in preventing infections at suture sites and catheter surfaces.

Drug-Eluting Sutures and Catheters

Antimicrobial systems from nature have increasingly used both the inherent bioactivity of materials and surface modifications to incorporate antimicrobial properties. Chitosan has been of great interest due to its cationic properties which disrupt microbial membrane integrity; fibers are also a beneficial platform as they have a large surface area that can hold immobilized antibiotics, peptides, nanoparticles, or plant-based compounds [39]. The goal of today's systems is to maintain long-lasting antimicrobial activity, minimize toxicity to cells, and reduce antibiotic use. These types of systems may be used to prevent infections around suture lines and catheter surfaces.

Future Perspectives

Opportunities for Next-Generation Natural Fiber-Based Devices

Next-generation devices may use combinations of natural fibers and bio-active coatings, drug-delivery components, reactive components, and engineered structures. Advanced silk, cellulose, chitosan and protein-based fibers could offer better mechanical properties (strength, flexibility), increased biodegradability and improved interactions with tissues [47]. Multifunctional sutures and catheter materials may provide mechanical support, antimicrobial protection, localized drug delivery, and promote wound healing on a single platform.

Integration with Nanotechnology and Biotechnology

The integration of nanotechnology and biotechnology provides control of fiber morphology, surface chemistry, biological interactions and therapeutic loading. Nanostructured coatings, nanoparticles, nanofibers, enzymes, peptides, and recombinant biomolecules can be integrated into the device to provide function while maintaining the benefits of the materials [73]. Integration of these technologies with bio fabrication can create devices that replicate the microenvironment of tissues and therefore provide applications.

Artificial Intelligence and Advanced Material Design

Natural-material discovery may be accelerated through artificial intelligence. This is accomplished by identifying relationships between composition, processing parameters, structure, and biological performance. Additionally, machine-learning models can provide predictions of material properties, optimize formulations, determine viable combinations of materials and assist in designing experiments. High throughput experimental databases could potentially decrease the amount of time needed to develop new materials and aid in the process of rationally selecting natural fibers based upon their application needs [74], [75].

Prospects for Clinical Translation

Clinical translation is dependent on several factors: reproducibility of raw materials; validation of manufacturing; ability to sterilize; predictability of degradation; safety; and adherence to regulatory requirements. Prior to adoption of a product, there must be evidence of standardized characterization and performance testing that has been validated. Through the collaboration of researchers, clinicians, manufacturers, and regulators, we can develop specifications and testing pathways for products. The evidence of safety, efficacy, consistency, and value of a product will ultimately dictate whether it is commercialized [76].



Figure 3. Future Development Pathway of Natural Fiber-Based Sutures and Catheters

CONCLUSION

The inherent biocompatibility, biodegradability, renewability, and potential biological activity of natural fibers makes them an attractive alternative to current petroleum based materials in the creation of future suture and catheter designs. In addition to their physical/chemical/functional properties which are well suited to use in medical devices, they may also be modified by; chemical modification, cross linking, blending with other polymers, functionalizing the surfaces of the fibers, electro spinning, utilizing nano technologies and creating composite structures to enhance their performance.

In spite of the potential benefits mentioned above, there are numerous obstacles such as batch-to-batch variation, moisture sensitivity, mechanical limitations, processing issues, changes caused by sterilization, and the unknown biodegradation of the polymer that create a barrier to commercialization of the technology. Therefore, standardized methods of extraction, characterization, manufacturing, sterilization, and quality control must be developed to provide consistency in the product's behavior. Innovative technologies using functional antimicrobial functionalization, drug eluting systems, "smart" materials, nanofibers, and advanced manufacturing techniques may lead to multi-functional sutures and catheters which will provide both physical support and infection control, as well as therapeutic delivery and tissue integration.

Future studies will need to focus on developing cost-effective, environmentally conscious production methods; performing both in vitro and in vivo evaluations; conducting predictive degradation analyses; and providing thorough regulatory validations. Additionally, the incorporation of Artificial Intelligence (AI), Biotechnology, and Advanced Materials Engineering may greatly enhance the speed at which we can identify new materials and optimize their properties. Overall, natural fiber-based biomaterials provide significant opportunities to create safe, multi-functional, and environmentally friendly biomedical devices that provide better outcomes for patients and have less of an effect on our environment.

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