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MINI REVIEW

Advance biodegradable jute fabric surface with water-repellent properties

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ABSTRACT

The increasing demand for sustainable materials has positioned jute as a prominent natural fiber due to its affordability and environmentally friendly properties. However, its application is limited by inherent drawbacks such as high moisture absorption, poor wettability, low thermal stability, and quality variability. These issues can be addressed by modifying jute surfaces to achieve water-repellent (hydrophobic/superhydrophobic) properties through physical and chemical treatments. This review offers a comprehensive overview of jute fabric sources and properties, exploring physical modification methods such as plasma and radiation treatments, and chemical methods including fluorination, silane coupling agents, sol-gel processes, polymer coatings, and nanoparticle coatings. These methods effectively reduce surface energy and introduce nanoscale roughness, resulting in water-repellent jute fabrics. Applications of modified jute include waterproof textiles, oil-water separation, moisture-resistant packaging, construction materials, and enhanced durability in composites. The study concludes with insights into the future prospects, advocating for the development of eco-friendly coatings that preserve jute's natural benefits while enhancing its performance in modern applications.

KEYWORDS

Natural fiber; Jute; Surface modification; Superhydrophobic

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Introduction

Natural-fiber-based materials have gained widespread acceptance due to growing environmental concerns and are increasingly being used as alternatives to synthetic materials [1]. These natural fibers offer benefits such as low cost, low density, and biodegradability [2]. However, their primary drawback is their hydrophilic nature, which creates incompatibility with hydrophobic polymer matrices and leads to agglomeration [3]. Additionally, natural fibers have poor moisture resistance, resulting in inferior mechanical properties and dimensional instability in composites [4].

Among natural fibers, jute stands out as one of the most affordable and is second only to cotton in cultivation [5]. India and Bangladesh are the dominant players in the global jute market, with India leading in production and Bangladesh excelling in exports. China, Thailand, the UK, and Vietnam also contribute to the global jute supply, albeit on a smaller scale [6,7]. Jute has a long history of use and is valued for its biodegradability, luster, air permeability, and excellent moisture absorption [7]. Traditionally used for making sacks, rope, woven carpets, and curtains, jute's applications have now expanded to include industrial products such as non-wovens, geotextiles, and fiber-reinforced composites [8]. Despite its wide range of uses, jute fiber has strong rigidity, low elongation at break, poor hydrophobicity, and limited spinnability, which hinder its industrial applications. For instance, hydrophilic jute fabrics have poor compatibility with hydrophobic resins, leading to their limited use [5,9,10]. Enhancing the hydrophobicity of jute fabrics is therefore crucial for improving their compatibility and surface properties.

To address these challenges, enhancing the hydrophobicity of jute surfaces to achieve superhydrophobicity has emerged as one of the most effective approaches. Surfaces are categorized based on their water contact angle (WCA) into four types: superhydrophilic (WCA $< 10°$), hydrophilic ($10° <$ WCA $< 90°$), hydrophobic ($90° <$ WCA $< 150°$), and superhydrophobic (WCA $> 150°$) [11,12]. Superhydrophobic surface coatings rely on both the surface roughness and its wettability. Achieving superhydrophobicity requires a combination of hierarchical micro-nano structures and low surface energy [11,13]. The hydrophilic properties of jute can be transformed into superhydrophobic characteristics by applying various surface modification techniques.

Applying suitable surface coatings is a promising approach to achieving superhydrophobicity on fabric surfaces [14]. These coatings provide water-repellent properties while preserving the environmental benefits of natural fibers like jute. Using biodegradable materials for these coatings minimizes the ecological footprint, meeting the demand for sustainable solutions. This comprehensive review aims to enhance jute fabric surface properties with superhydrophobic coatings, bridging functionality, and sustainability. Innovative surface modification can make jute more versatile and resilient, suitable for modern applications while maintaining its eco-friendly appeal.

Scope of the Review

This review article explores the enhancement of jute fabric surface properties through the application of biodegradable superhydrophobic coatings. It covers the sources and properties of jute fibers, the principles, and materials used for water-repellent coatings, and various physical and chemical surface modification techniques. The article also discussed the applications of surface-modified jute, highlighting its

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potential in waterproof textiles, oil-water separation, packaging, construction, and composite materials. Prospects and conclusions are discussed, aiming to bridge functionality and sustainability in jute fabric advancements. The focus of the review is illustrated schematically in Figure 1.

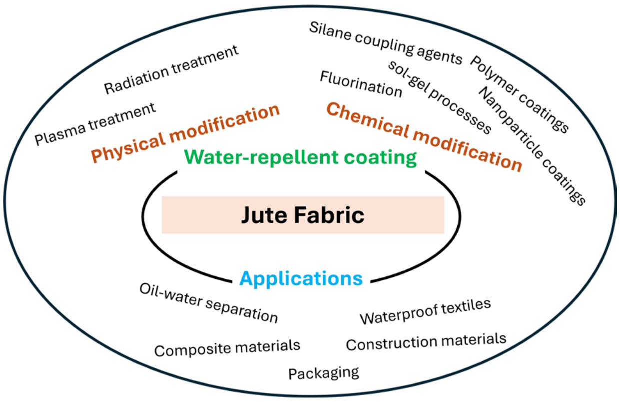

Figure 1. Focus of the review.

Jute Fibers: Sources and Properties

Jute, an essential natural fiber commonly known as lignocellulosic fiber, is widely cultivated in India and Bangladesh [7]. It is also known as the "Golden Fiber" and is gaining attention due to its excellent properties, including high moisture absorption and affordability [15,16]. The jute plant grows to a height of 2.5-3.5 meters in approximately 3-6 months, after which the fibers can be extracted through the retting process [17]. It is primarily sourced from the plants *Corchorus olitorius* and *Corchorus capsularis*, which thrive in warm, humid climates with ample rainfall regions. Jute fibers, golden to brown in color, exhibit a silky sheen and high tensile strength (399-773 MPa) with an elongation break of 7-8%. The high cellulose content (59-71%) of jute ensures durability, while its lignin (12-13%) and hemicellulose (14-20%) contribute to rigidity and moisture absorption [17]. With low thermal conductivity and decomposition beginning around 150 °C, jute is fully biodegradable, making it an eco-friendly material. Extensively used in textiles, composites, geotextiles, and home decor, jute fibers are sustainable, renewable, and play a significant role in various industries due to their strength, biodegradability, and environmental benefits.

Superhydrophobic Coatings

Jute fabric, while eco-friendly and affordable, has several shortcomings, including poor durability, high moisture sensitivity, stiffness, a limited color range, and rapid environmental degradation [7,8]. These issues can be mitigated by applying superhydrophobic coatings to the fabric. Such coatings enhance durability by making the fabric water-repellent, significantly reducing moisture absorption and extending its lifespan [3,11]. This water resistance also protects the fabric from mold and mildew growth, ensuring better hygiene and longevity. Additionally, superhydrophobic coatings can make the fabric less stiff and more comfortable for use in clothing and other applications. They also prevent liquids from penetrating the fabric, making it resistant to stains and easier to clean. As a result, jute fabric with these coatings can be used in a broader range of applications, including outdoor furniture and clothing where water resistance is crucial. Moreover, by extending the life and utility of jute fabric, superhydrophobic coatings contribute to more sustainable consumption practices by reducing waste and the need for frequent replacements [18].

While a range of coating materials has been reported previously, the use of biodegradable options that minimize environmental impact after disposal is crucial. Consequently, researchers are focusing on developing such coatings to address the shortcomings of jute fabric and enhance its suitability for practical applications. When preparing a superhydrophobic surface, two key considerations should be made: first, selecting low surface energy materials, and second, introducing surface roughness and texture [11]. Superhydrophobic surfaces are typically grafted with low-energy functional groups, such as nitrogen-containing and fluorine-containing groups.

Surface Modifications of Jute Fabrics

Many surface modification techniques are employed to enhance the physical, chemical, and mechanical properties of natural fabrics [1,19]. These modifications improve durability, water and stain resistance, and antimicrobial properties, making the fabrics longer-lasting, easier to maintain, and more hygienic [20,21]. Enhanced UV protection and fire resistance make them safer for outdoor and home use [22]. Improved adhesion and mechanical properties increase their suitability for demanding applications, while self-cleaning abilities reduce maintenance needs [23]. Aesthetic enhancements, such as gloss and color vibrancy, add value for fashion and design. Surface treatments can also enhance thermal regulation, making fabrics more comfortable in various climates. Many modification techniques are eco-friendly, supporting the demand for sustainable products. Surface modification methods can be broadly categorized into physical and chemical techniques [19]. Physical modification techniques aim to alter the fabric's structural and surface properties without changing its chemical composition. However, chemical modifications of jute fabric occur mostly through the formation of covalent bonds between the fabric functionality and the functional groups in the coating agents. It is important to note that not all these methods are eco-friendly, so potential environmental hazards must be considered before their application. Some modification techniques may not be suitable for certain applications, such as in the food packaging industry. This section provides a brief overview of a few important surface modification techniques.

Physical modification techniques

To enhance the jute fabric surface, particularly for developing superhydrophobic surfaces, several physical modification techniques can be employed. These techniques aim to alter the fabric's structural and surface properties without changing its chemical composition. Here are some common physical modification techniques that are discussed below.

Plasma treatment

Plasma treatment effectively modifies jute fabric surfaces to create superhydrophobic properties [24]. The process involves exposing the fabric to a plasma field of energetic ions, electrons, and neutral particles, altering its surface chemistry and topography without significantly affecting the bulk material. Initially, the jute is cleaned and placed in a plasma reactor, where it encounters a low-pressure plasma field generated by electric discharge [25]. Various gases, such as oxygen, nitrogen, and fluorine-containing gases, are used to modify the surface

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[7]. Oxygen plasma introduces hydrophilic functional groups, while fluorine-based gases graft low-energy groups, resulting in superhydrophobic properties. Plasma treatment uniformly modifies complex surfaces, is environmentally friendly, and allows precise control over surface properties. Plasma-treated jute fabrics demonstrate excellent water repellency with contact angles exceeding 150°, suitable for water-resistant textiles and packaging. However, the technique has low selectivity and high equipment costs.

Radiation treatment

Radiation treatment, using high-energy sources like ultraviolet (UV) or gamma rays, effectively creates superhydrophobic surfaces on jute fabric [17,26]. The process begins with cleaning the fabric, followed by exposure to radiation, which induces chemical changes and generates reactive sites on the surface. These sites are then functionalized with low-surface-energy substances, such as fluorinated compounds, to form a rough, hydrophobic layer that repels water. This method offers uniform surface modification, environmental benefits, and precise control over hydrophobic properties, though it requires specialized equipment and careful management of exposure conditions. Studies have shown that radiation treatment followed by a chemical treatment can significantly enhance the water-repellent properties of the treated surface.

Recently, Jha et al. showed an efficient, single-step method using high-energy gamma radiation to attach long-chain hydrocarbon molecules such as butyl methacrylate, octyl acrylate, and lauryl methacrylate, with lauryl methacrylate proving most effective [27]. Optimal reaction parameters, including total dose, dose rate, monomer concentration, and solvent, were established, showing no significant damage to the fiber's structure. Scanning electron microscopy confirmed successful grafting and fiber integrity. The lauryl methacrylate-modified jute can effectively separate oily liquids from water, enhancing its potential uses.

Chemical modification techniques

To achieve superhydrophobicity, chemical modification is frequently used to lower surface energy and introduce nanoscale roughness. Various chemical modification techniques are employed to enhance the water-repellent properties of jute fabric, as discussed below.

Fluorination

Fluorination involves the application of fluorinated compounds to the natural fabric through methods like dip-coating, spray-coating, or chemical vapor deposition [7,28]. Chemicals such as perfluorooctyltriethoxysilane (PFOTES) and perfluorooctanoic acid (PFOA) are commonly used. These compounds create a surface that exhibits extremely low surface energy, making the jute fabric highly water-repellent. The fluorinated molecules align themselves in such a way that their hydrophobic tails point outward, effectively repelling water and oils. This treatment can result in a fabric that not only repels water but also resists staining from oils and other non-polar liquids.

Silane coupling agents

Another effective method employs silane coupling agents like hexadecyltrimethoxysilane (HDTMS) or fluoroalkylsilane [29]. These agents are used to graft hydrophobic molecules onto the jute fibers [30]. The process typically involves immersing the fabric in a solution containing the silane coupling agent, which reacts with the hydroxyl groups on the cellulose molecules in the jute. This reaction forms a covalent bond, creating a monolayer of hydrophobic molecules on the fiber surface. The result is a significant reduction in surface energy, which imparts water-repellent properties to the fabric.

Sol-gel process

The sol-gel process involves the creation of a silica-based network on the fabric surface through the hydrolysis and condensation of alkoxysilanes, such as tetraethoxysilane (TEOS) and 1,1,1,3,3,3-hexamethyl disilazane (HMDS) [31]. The process starts with the preparation of a sol, a colloidal suspension of nanoparticles, which is then applied to the jute fabric. As the sol undergoes gelation, it forms a porous, three-dimensional network of silica. This network can be functionalized with hydrophobic groups, such as alkyl or fluoroalkyl chains, to achieve superhydrophobicity. The resulting silica network provides both nanoscale roughness and low surface energy, crucial for superhydrophobic behavior.

Polymer coating

Polymer coatings using substances like polydimethylsiloxane (PDMS) or polytetrafluoroethylene (PTFE) are applied to the jute fabric through methods like dip-coating, spray-coating, or electrospinning [32]. PDMS, a silicone-based polymer, forms a flexible, hydrophobic layer that can conform to the fabric's texture. PTFE, commonly known as Teflon, provides a durable and highly water-repellent coating. These polymer coatings create a continuous hydrophobic layer on the jute fabric, effectively preventing water penetration while maintaining the fabric's flexibility and breathability.

Nanoparticle coating

Nanoparticle coating methods, such as dip-coating, spray-coating, or in situ growth, involve the use of hydrophobic nanoparticles such as silica or titanium dioxide (TiO_2) [33,34]. These nanoparticles create a rough surface texture that is essential for superhydrophobicity. The nanoparticles can be functionalized with hydrophobic molecules, such as alkyl or fluoroalkyl chains, to further enhance water repellency. The combination of nanoscale roughness and low surface energy provided by the functionalized nanoparticles contributes to the fabric's superhydrophobic properties.

The combination of these techniques can be tailored to achieve the desired level of superhydrophobicity while maintaining the mechanical properties and breathability of the jute fabric. The choice of method depends on specific application requirements, environmental considerations, and the desired durability of the coating. Each technique offers unique advantages and can be selected based on the specific needs of the application, ensuring optimal performance of the superhydrophobic jute fabric.

Applications of Surface-Modified Jute

Surface-modified superhydrophobic jute has gained significant interest for its unique properties and diverse applications. By modifying the surface of jute to achieve superhydrophobicity, the natural fiber is endowed with water-repellent characteristics, opening numerous potential uses. Here are some key applications:

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Waterproof textiles

Superhydrophobic jute can be used to create waterproof textiles, which are particularly valuable in the fashion and outdoor gear industries. Clothes, shoes, and accessories made from this material can repel water, keeping the wearer dry in wet conditions. This is especially useful for raincoats, jackets, and tents. Khatton et al. [35], developed water-repellent jute fabrics by treating them with varying ratios of Nova TTC (a fluorocarbon compound) to determine the best formulation. The treated fabrics exhibited excellent water repellency, making them suitable for various jute products in diverse textile applications.

Oil-water separation

Superhydrophobic jute has promising applications in environmental protection, particularly in oil spill cleanups [8]. The material can selectively absorb oils while repelling water, making it an effective tool for separating oil from water bodies. This characteristic is useful for treating industrial wastewater and marine water containing oil contaminants. Recently, Srishti et al. [36], developed superhydrophobic jute fabric with a WCA of ~159° by incorporating TiO_2 nanoparticles and hexadecyltrimethoxysilane (HDTMS) using a drop-casting method. This modified jute fabric acts as a high-performance, reusable filter for oil-water separation, effective in challenging environments such as acidic, alkaline, saline, and extreme temperatures. It shows high separation efficiency, recyclability, and durability, demonstrating significant potential for practical applications.

Packaging materials

Biodegradable natural fabric can be used in the packaging industry to create moisture-resistant packaging materials [37]. Such materials are ideal for protecting goods from water damage during shipping and storage. This is particularly useful for food products, electronics, and other moisture-sensitive items.

Post-harvest grain storage is vital for food security, but jute bags, common in developing countries, are prone to moisture, leading to fungal growth and seed spoilage. Odokonyero et. al. [38], addressed this by modifying jute bags with alkali and wax treatments, creating wax-coated jute bags (WCJBs) that are significantly more water-repellent. In a 2-month wheat storage experiment at varying humidity levels, WCJBs reduced seed moisture content by 4-7.5% and improved germination rates by 12-35% compared to untreated bags. This innovation could significantly reduce post-harvest losses in regions reliant on jute bags for grain storage.

Srishti et al. [39], chemically treated jute to make it water-resistant (WCA ~162°). The coated jute demonstrated high mechanical durability, lasting over a month in the air, enduring 6 hours of ultrasonic washing, over 50 brush scrubbing cycles, and more than 150 mutual abrasion cycles, while also showing good thermal stability. In a 2-month seed storage experiment at 85% relative humidity, wheat grains in the coated jute bag had 8.08% less moisture content than those in a control bag. The control jute showed changes in color, texture, and fungal development. Additionally, the coated jute reduced bacterial growth by over 50% in 48 hours. This jute offers a sustainable packaging solution, promoting eco-friendly practices and reducing plastic waste.

Construction and building materials

Superhydrophobic jute can be used in the construction industry to create water-resistant building materials. For instance, jute-based composites and panels can be used for roofing, insulation, and wall cladding, providing protection against water ingress and enhancing the durability of structures.

Srishti et al., developed a jute-based geotextile with exceptional water repellency (169° WCA) and consistent tensile strength (~12 MPa) by incorporating HDTMS-modified TiO_2 nanoparticles using a drop casting technique. The coating's durability was tested with sand abrasion, impact tests, immersion in various aqueous media, and thermal degradation assessments. Biodegradability was evaluated by burying samples in soil for different periods. The results indicate that the HDTMS-TiO_2 coating provides mechanically durable and sustainable superhydrophobic properties, making it suitable for roadway applications.

Enhanced durability in composite materials

By incorporating water-repellent jute into composite materials, the durability and lifespan of the composites can be enhanced [18]. These composites can be used in various industries, including automotive, aerospace, and sports equipment, where lightweight and durable materials are essential.

Dong et al. [41], investigated the laccase-mediated grafting of dodecyl gallate (DG) onto jute fiber. The grafting products were appropriately characterized, and the grafting percentage and DG content in the modified jute were determined through weighing and saponification, respectively. Hydrophobicity was assessed by contact angle and wetting time, and the mechanical properties and fracture section of jute fabric/polypropylene (PP) composites were studied. Results showed covalent coupling of DG to jute, with a maximum grafting rate of 4.16% under specific conditions (80/20 pH 3 acetate buffer/ethanol, 1.0 U/mL laccase, 5 mM DG, 50 °C, 4 h). The modified jute had increased hydrophobicity with a WCA of 111.49º and enhanced breaking strength with a neat and regular fracture section.

Modifying jute to make it water-repellent significantly enhances its properties and expands its applications. From environmental protection to construction and textiles, superhydrophobic jute provides innovative solutions across various sectors, leveraging its natural abundance and sustainability.

Conclusions and Future Prospects

The primary aim of this review is to encourage researchers to explore the potential of jute fibers as an alternative to synthetic fibers. To address jute's common shortcomings, such as moisture absorption, poor wettability, low thermal stability, and quality variability; a water-repellent coating on the jute surface is essential. This review provides a detailed discussion of important physical and chemical modification techniques. It reveals that combining these methods can achieve the desired water-repellent properties while preserving mechanical strength. The choice of technique should be based on specific application requirements, environmental considerations, and desired coating durability. While superhydrophobic jute has potential applications in waterproof textiles, oil-water separation, packaging, construction, and composites, many areas remain underexplored, often limited to lab-scale studies. Further research is needed to assess industrial applicability and

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to investigate potential developments in biomedical applications, fire resistance, and antimicrobial properties.

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Disclosure statement

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