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Optimization of Jute Fiber Surface Treatment via Integrated Approach: A Conceptual Review

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***Abstract*—** *The review paper highlights the low cost and biodegradability of jute as a sustainable substitute for synthetic fibers. It examines the impact of several surface modification techniques on the morphology, crystallinity, and interfacial behavior of jute, including alkali, silane, plasma, bleaching, and benzoylation. Alkali treatment increases crystallinity but does not lessen hydrophilicity. Benzoylation and silane enhance interfacial bonding but have no influence on mechanical strength. Roughness and activation are improved by plasma treatment; however, hydrophilicity is not addressed. In addition to a unique silane-plasma treatment worth investigating, the research suggests synergistic techniques, especially the alkali-silane combination, which enhances hydrophobicity and tensile strength. In general, it provides information about creating composites with sustainable fiber reinforcement.*

I. INTRODUCTION

Environmental issues have become a major concern in recent years. The depletion of natural resources and various forms of pollution, including air, water, and soil pollution, are the reasons why every country in the world is looking for creative ways to promote alternative fuels to lower the global carbon footprint. The idea of sustainable development, which is essential to the welfare of both the current and future generations, lies at the heart of this endeavor. One of the most sustainable alternatives for it is the use of eco-friendly materials (Elfaleh et al., 2023). Composites made of natural fiber are a wise decision from an ecological and financial standpoint. These composites have outstanding mechanical qualities and are recyclable and renewable (Jaafar et al., 2019). Bast fibers (jute, flax, ramie, hemp and kenaf), seed fibers (cotton and kapok), leaf fibers (sisal, pineapple and abaca), and grass and reed fibers (rice, corn and wheat) are the different categories of natural fibers. They may also originate from roots and wood. Baskets, ropes, mats, and other household goods can be made with these fibers. Fiber reinforcement composites have a wide range of uses in the present period, including seat backs, interior pillars, automobile door panels, and thermal insulation (Mohammed et al., 2015).

Among all the fibers, jute is particularly popular in the Indian subcontinent because of its many applications and biodegradability. Jute is an inexpensive, high-yield crop with exceptional resilience and light weight in Bangladesh. Despite its potential economic worth, it has drawbacks such as subpar mechanical qualities. When fiber is used as a

reinforcing material in a composite, the effect is crucial. Its use in composites is severely limited by poor interfacial bonding. Reduced surface smoothness, flexibility, and fiber fineness are caused by the noncellulosic components (hemicellulose, lignin, waxes, and oils) (Islam et al., 2022; Sarker et al., 2019). Due to the abundance of hydroxyl groups in cellulose, jute fibers are highly hydrophilic, making them susceptible to moisture, which can cause fiber deterioration and diminished physico-mechanical characteristics (Sinha et al., 2017). There are several surface treatment techniques available to overcome these constraints and enhance the fiber–matrix interfacial adhesion. Alkali treatment is the most often utilized and well-liked of all. The elimination of non-cellulosic parts, which helps reduce the microfibril angle and boost load-bearing ability, is the fundamental idea of alkali treatment. Other surface alterations like acetylation, silanization, benzoylation, bleaching, and plasma treatment have all demonstrated promise in addition to alkali treatment. However, cost or compatibility concerns, may restrict their use (Chandrasekar et al., 2017; Islam et al., 2022).

The application of combination or synergistic surface modification techniques, which are frequently based on alkali treatment, is a potential strategy to get beyond the limitations of single-treatment approaches. Although alkali treatment is thought to be a relatively non-destructive technique that maintains the intrinsic structure of jute fibers while eliminating impurities and enhancing surface roughness, it also makes the fiber more hydrophilic, which is undesirable for composite applications because of increased moisture absorption. After alkali treatment, further treatments, including benzoylation and silanization, are used to improve compatibility with hydrophobic matrix and decrease hydrophilicity. Thus, a more balanced change is produced by the synergistic combination of various treatments, which improves fiber performance overall (Khalid et al., 2021a). This study compiled research from 2014 to 2025; the focus was on different surface treatments, the influence of treatment parameters on fiber properties, and also critically different combined treatments available, particularly for jute fiber. The discussion was detailed and comprehensive. The synergistic approach between different treatments can provide a new direction for this research field.

II. JUTE FIBER GENESIS

Jute is an herbaceous shrub that grows quickly and belongs to the Corchorus genus in the Tiliaceae family. It grows well in places like Nepal, China, Indonesia, and portions of South America, and it is widely grown in Bangladesh and India. *Corchorus olitorius*. and *Corchorus capsularis*, the two main commercially significant species, originated in distinct areas. While *C. olitorius* most likely evolved in the Indo-Myanmar region, *C. capsularis* is believed to have originated in the equatorial regions of East Africa. After arriving in Asia, both species were domesticated, especially in the rich soils of the Indian subcontinent (Kaysar et al., 2022; Mukul et al., 2021). The important strands of jute, a bast fiber, are found in a layer known as the "phloem" beneath the bark of the plant stalk. The procedure of retting is used to remove these resilient natural fibers. Several variables, including growing circumstances, harvest time, maturity, and the efficiency of decortication and post-retting cleaning, affect the quality of jute fiber. The subject of sustainable material science is still interested in bast fibers, such as jute, because of its exceptional mechanical strength (Palanisamy et al., 2022; Zhu et al., 2024).

JUTE FIBER MORPHOLOGY

(A) Jute Structure The jute fiber stem is made up of a dense, hollow, woody core surrounded by multiple interconnected cell bundles called ultimate cells. These bundles are bonded by a pectin-based matrix, which is degraded during the retting process. The ultimate cell bundles, referred to as reeds, form a mesh-like network that acts as the main structural framework of the fiber. Importantly, a jute reed is not a single cell; it is a bundle consisting of approximately 5–15 smaller cell units. These units are joined together laterally and along the length of the fiber through intercellular materials, which are predominantly non-cellulosic. At the level of the ultimate cell wall, two distinct layers are present: a thin outer primary wall and a thicker inner secondary wall. Each layer has a different molecular structure, though both are composed of fine microfibrils. In the primary wall, the microfibrils follow a crisscross arrangement, whereas in the secondary wall, they are oriented more parallel to one another. Within the ultimate cells, cellulose forms the main microfibrillar phase and is highly organized in specific regions. The spaces between microfibrils are filled largely with short-chain hemicellulose and a portion of lignin. The microfibrils in the jute cell wall are arranged in a right-handed spiral, making an angle of about 7–9° with the fiber axis. This spiral arrangement helps explain the fiber's high strength, high initial modulus, and low extensibility (Roy,

2010). The schematic representation of the jute fiber is shown below in Fig. 1.

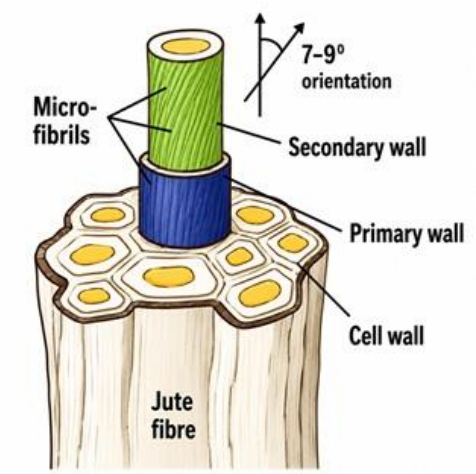


Fig 1. Jute fiber structure (Shuvo, 2020)

(B) Chemical Composition Jute fiber is primarily composed of cellulose (60–70%), hemicellulose (12–14%), and lignin (5–10%), alongside components like wax and pectin. Table 1 shows the different compositions of jute according to different sources. FTIR analyses effectively characterize its structure, revealing functional groups and arrangement. Research by (Shahinur et al., 2020) indicated that FTIR spectra (Fig 2) show hydroxyl (–OH) groups associated with cellulose and hemicellulose, within the range of 3680–3200cm^{-1}, confirming the hydrophilic nature of jute fibers due to hydrogen bonding. Specifically, a peak around 3428 cm^{-1} is linked to O–H stretching, and a peak near 2920 cm^{-1} reflects C–H stretching in cellulose chains. Additionally, the lignin-related absorption near 1648cm^{-1}, along with C–H stretching measurements in the 3300–2700cm^{-1} range, suggest that these characteristics intensify with increased temperature and retting time. This data emphasizes that cellulose serves as the backbone of jute fiber, with hemicellulose and lignin playing key roles in matrix binding and contributing to its amorphous traits.

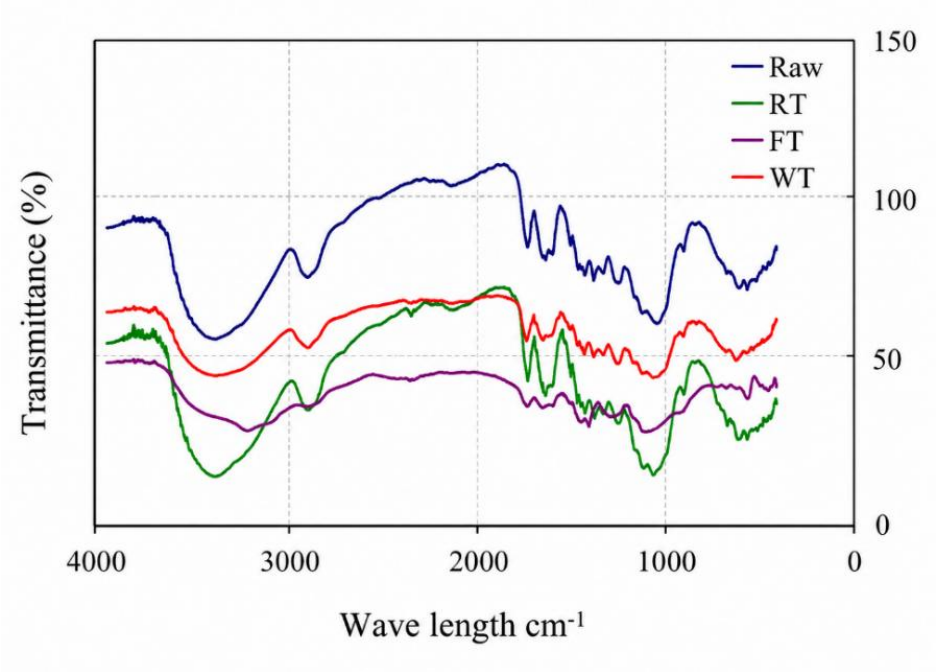


Fig 2. FTIR analysis of raw and treated jute fiber (Shahinur et al., 2020); RT= Rot-retardant treatment, FT= fire-retardant treatment, and WT= water-retardant treatment.

JUTE FIBER PROPERTIES

The mechanical qualities of jute fiber are the result of a complex interaction between several factors, including its maturity, cultivation circumstances, structural features, and extraction techniques. Even though cellulose is important, jute has roughly 60% cellulose, whereas cotton has 90%, but this does not explain why jute is stronger than cotton. These phenomena can be explained by the fact that jute can tolerate higher stress because of its smaller microfibril angle (7-8°) compared to cotton's 20–30°. Furthermore, jute's elasticity is enhanced by its bigger amorphous region, which enables it to support higher loads without breaking (Khan, 2015; Komuraiah et al., 2017)

Table 1: The constituents of jute fiber.

Jute fiber constituent				
Cellulose (%)	**Hemicellulose (%)**	**Lignin (%)**	**Wax & pectin (%)**	**Reference**
45-71.5%	13.6-21%	12-26%	0.2 (only wax)	(Chandekar et al., 2020; Wang et al., 2019)
61-73%	13.6-23%	12-16%	-	(Farzana et al., 2022)
61–71.5	12.0–20.4	11.8–13	0.7	(Sahu & Gupta, 2020a)

The influence of fiber length significantly impacts composite manufacturing, with research by Sajin et al. indicating that shorter to medium-length fibers (5 mm to 25 mm) can enhance stress distribution and minimize defects more effectively than longer fibers. Among these, 5 mm fibers exhibit superior mechanical properties. Jute fibers are noted for their strength, exhibiting a tenacity range of 4.2 to 6.3 gf/denier, although this tenacity fluctuates based on fiber length. The elongation at break for jute fibers ranges from 1.0% to 1.8%, and they are limited to elastic deformation, breaking before reaching the plastic deformation stage. Additionally, jute fibers demonstrate high resilience, recovering 75% of their original length after being strained by 1.5%, along with impressive flexural and torsional rigidity compared to wool and cotton (Sanyal, 2017)

One of the most crucial and vital characteristics of natural fibers is their hydrophilicity. Twelve percent of the weight of jute is absorbed by the fiber itself. The use of jute in fiber reinforcement composites makes this significant (Ali et al., 2018). Moisture causes instability and decreased fiber matrix bonding during composite production. Long-term mechanical performance declines even if this trait is beneficial in some areas, such as the construction and automobile packaging sectors (Arunachalam et al., 2026). The hydrophilicity of jute fibers can be decreased by several treatments, including plasma treatment, silane treatment, and other surface modification methods. The goals of these treatments are to decrease moisture absorption and enhance fiber-matrix compatibility. The sections that follow will provide an explanation of these treatments in brief.

Jute is thought to have strong thermal properties. Jute does not melt at high temperatures; instead, it burns and forms char because it is not thermoplastic. Jute has good thermal insulation with a heat capacity of about 1360 J/kg·K. However, its applications are limited due to its low ignition temperature (Roy, 2010). In composite applications, thermal characteristics are crucial. The thermal conductivity of composites reinforced with jute and banana fibers with varying fiber volume fractions was compared by (Subramanya et al., 2017). The findings verified that both composites' thermal conductivity decreases with increasing fiber content. Fiber direction within the matrix affects thermal characteristics as well. The 45° angled fiber in the matrix demonstrated superior flame resistance, according to (Sathish et al., 2015) experiments with fibers organized in various orientations.

SURFACE TREATMENT

(A) Plasma Treatment One of the most efficient and sophisticated methods for surface modification, particularly for natural fiber, is plasma, which uses ionized gas with electrons, ions, and neutral species to change surface properties without changing the bulk surface. Its significance in composite applications is highlighted by a few studies. For example, (Morshed et al., 2010) found that by removing amorphous parts from hemicellulose, plasma treatment enhanced crystallinity. There was an increase in the relative cellulose content. According to (Nyssanbek et al., 2024), this structural alteration enhanced mechanical strength, boosted biodegradability, and improved interfacial adhesive bonding with the polymer matrix.

There are two types of plasma systems: thermal (hot) and non-thermal (cold). Their operational circumstances and material processing suitability are the basis for the classification. Thermal plasma functions at temperatures higher than 1000 K in (Singh et al., 2024) research. This gives it the moniker "hot plasma," which restricts its employment in biopolymers that are sensitive to temperature, such as jute fiber, due to the possibility of thermal deterioration. Conversely, cold plasma is commonly used to modify natural fibers. Furthermore, the study shows that although thermal plasma offers great energy and a quick surface change, it is not appropriate for delicate fibers like jute. Cold plasma, on the other hand, allows for controlled surface change without seriously harming the surface.

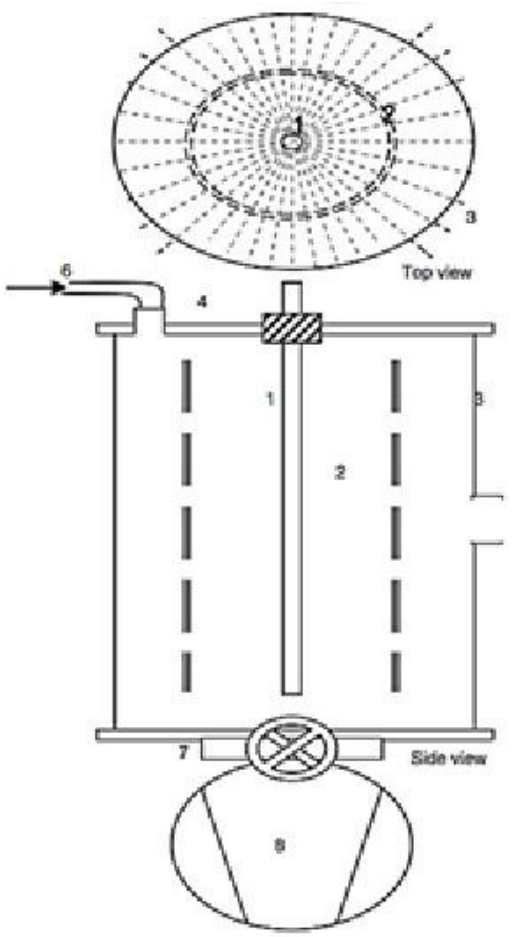


Fig 3. An experimental plasma chamber. (1) Water-cooled tube (Cathode); (2) Jute fibers; (3) stainless steel chamber (anode); (4) electrical lead through; (5) view-port; (6) gas inlet needle valve; (7) isolation gate valve; (8) vacuum pumping system (Sinha, 2009).

The experimental settings of cold plasma produced in a vacuum chamber with argon gas at a pressure of roughly 10^{-1}mbar and a modest DC power input (~20 W) (Seki et al. 2010). A plasma chamber is the configuration that allows for stable plasma formation appropriate for surface treatment of jute fibers by using the chamber wall as the anode and a centrally located electrode as the cathode (Fig 3). When applied to natural fibers, plasma treatment eliminates non-cellulosic components like lignin and hemicellulose while leaving cellulose largely intact. By increasing cellulose exposure and enhancing overall crystallinity, this selective ablation improves wettability and lessens the aging effect during storage characteristics (Shahzad, 2009). According to Sinha (2009) surface properties, untreated jute fiber usually has a water contact angle of about 80°, which reflects its natural hydrophilicity. An increase in contact angle has been regularly seen after plasma treatment, suggesting a change toward hydrophobic behavior. This modification improves fiber-matrix adhesion in composite systems by greatly increasing compatibility with the hydrophobic polymer matrix.

(B) Alkaline treatment The simplest and most efficient natural fiber treatment is alkaline. Sodium hydroxide (NaOH) is widely utilized for various natural fiber treatments. Fiber performance, shape, and chemical composition are all impacted by alkali treatment. However, the treatment conditions, specifically the NaOH concentration and exposure duration, have a significant impact on its efficacy (Sanivada et al., 2026). At the chemical level, the treatment follows a specific reaction mechanism (Equation 1) involving the transformation of hydroxyl groups (Fiber-OH) into alkoxide groups (Fiber-ONa), which facilitates the removal of lignin, hemicellulose, pectin, waxes, and oils (Verma & Goh, 2021).

$$\text{Fiber-OH} + \text{NaOH} \rightarrow \text{Fiber-ONa} + H_2O$$

(Equation 1)

Several studies have examined the effects of alkaline treatment on natural fibers, particularly focusing on jute. Sahu & Gupta, 2020 found that a 5% alkali concentration at room temperature for 48 hours yielded optimal results for jute fiber. (Islam et al., 2022) determined that treating jute fibers with a 5% NaOH solution for 4 to 6 h produced the best outcomes, resulting in a significant increase in the crystallinity index, reaching up to 68%. However, treatments extending beyond 6 h led to a notable decline in flexibility, marked by a 23% reduction in breaking strain, which indicated increased brittleness. (Wang et al., 2019) corroborated these findings, reporting an optimum cellulose content of 75.52% at a 6% NaOH concentration, with improvements in related properties evident at concentrations between 6% and 8%. Nevertheless, increasing the concentration to 10% caused surface degradation and peeling of the fiber structure.

The improvement in physical and mechanical properties due to alkali treatment of jute fiber is attributed to changes in fiber morphology and structure. The treatment causes a significant loss of hemicellulose, along with some lignin, waxes, and oils, resulting in a cleaner and rougher fiber surface. This enhanced roughness fosters better mechanical interlocking between the fiber and the matrix. Moreover, the removal of non-cellulosic components leads to a rearrangement of the fibers, making them more ordered and closely packed. This process reduces the microfibril angle, increases the crystallinity index, and promotes

stronger hydrogen bonding, which ultimately enhances the fiber's stiffness and tensile strength (Kar et al., 2023; Wang et al., 2019).

(C) Bleaching treatments The most common method for removing the natural color of lignocellulosic fibers, which are mainly made up of cellulose, lignin, and hemicellulose, is bleaching. Although this technique was once used primarily for aesthetic purposes, it is now being used for other objectives. Bleaching effectively eliminates coloring compounds, including unsaturated aldehydes, ketones, phenolic ring-conjugated ethylenic structures, and carbonyl-containing groups present in lignin from jute, a form of lignocellulosic fiber. The bleaching mechanism is given below in Equation 2 and Equation 3.

$H_2O_2 \rightarrow H^+ + HO^{2-}$ (Equation 2)

HO^{2-}+Jute fiber →White Jute (Equation 3)

In addition to eliminating cellulose and lignin, the bleaching procedure improves mechanical qualities by raising the fibers' fineness, breaking toughness, and breaking extension (Wang et al., 2019).

Over time, chlorine and its derivatives have been used as bleaching agents; however, due to their hazardous nature, alternatives have been explored. Three promising options include enzymes, ozone, and hydrogen peroxide, with hydrogen peroxide being identified as the most promising bleaching agent (Basak et al., 2018). Research has demonstrated that traditional peroxide bleaching improves whiteness but compromises fiber tenacity, requiring high temperatures and alkaline conditions that can damage fibers. (Chattopadhyay et al., 2022) proposed a peracetic acid bleaching process that achieves a whiteness index of 65.8 to 77.7 while maintaining up to 85% bundle strength. This process, performed at 70°C using 20 g/l peracetic acid for 120 minutes, highlights a significant innovation in bleaching. Furthermore, (Islam et al., 2025) indicates that under specific conditions of 2M concentration at 50-60°C for 120 min, a maximum crystallinity index of 75.34% can be reached. (Chattopadhyay et al., 2025) also notes the effectiveness of using the bleaching bath twice, resulting in a satisfactory whiteness index of 54.2–64.1 even after reuse, further enhanced by mild scouring treatments.

(D) Silane treatment A popular surface modification method to strengthen the connection between the fiber and matrix surface is silane treatment. Here, the silicon molecule is joined to both hydrophilic and hydrophobic components to form silane (SiH_4), an inorganic chemical. The general chemical formula for silanes is R(4-n)-Si-$(R'X)_n$ (n = 1,2), where X is an organofunctional group (such as amino, methacrylate, epoxy, vinyl, etc.), R is the hydrolysable group (such as ethoxy, acetoxy, methoxy, etc.), and R' is the alkyl bond that joins the silicon atom to the organofunctional group (Nor et al., 2023). Two well-known silane coupling agents for fiber treatment are bis [3-(triethoxysilyl) propyl] tetrasulphide (Silane 69) and 3-aminopropyl triethoxysilane (APTS). (Lakshmaiya et al., 2025; Liyana Mamauod et al., 2018)

The treatment mechanism is very interesting. For natural fiber, silane treatment process is divided into three stages: hydrolysis, condensation, and bond formation. Initially, silane coupling agents are non-reactive, but in the presence of moisture, alkoxy groups (-OR′) are hydrolyzed and become silanol groups (-Si-OH) (Equation 4). The silanol groups are unstable and tend to react with each other through condensation reactions, producing siloxane bonds (Si-O-Si). Jute fiber (cellulose) hydroxyl groups (-OH) (Equation 5) react with the silanol groups through a condensation process to produce covalent bonds (Equ. 6) (Koohestani et al., 2018).

$R\text{-}Si(OR')_3 + 3H_2O \rightarrow R\text{-}Si(OH)_3 + 3R'OH$

(Equation 4)

$Si\text{-}OH + Si\text{-}OH \rightarrow Si\text{-}O\text{-}Si + H_2O$

(Equation 5)

$R\text{-}Si(OH)_3 + Fiber\text{-}OH \rightarrow RSi(OH)_2O\text{-}Fiber + H_2O$

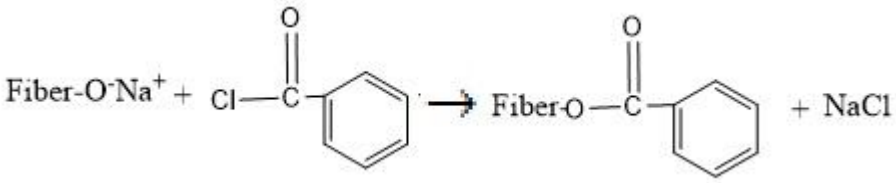
(Equation 6)

Silanes can be used in treatment either alone or in combination with alkali treatments, enhancing the properties of natural fibers like sisal and jute. (Orue et al., 2018) describes a process where sisal fibers are sonicated for three hours before being immersed in a 2% silane solution at pH 3-4 for another 3 h, followed by a 12 h drying period. Alkali treatment consists of two stages: initially treating fibers with 2 wt% NaOH for 12 h, leading to mild swelling, followed by a more intense treatment with 7.5 wt% NaOH under reflux for 90 min, removing substantial lignin and hemicellulose, and resulting in finer individual fibers. The alkali-silane combination is particularly effective for creating composites, as alkali treatment structures voids that silane can fill, resulting in stronger interlocks and improved tensile strength (Zafar et al., 2016) found that combining NaOH with 5 wt% APTS for jute fibers decreased crystallinity and tensile strength compared to alkali treatment alone, as silane interacts with edges of crystalline regions. Despite this reduction in crystallinity, it enhances flexibility, which is advantageous over brittle fibers. Additionally, the alkali-silane treatments improve

thermal properties due to better branching and siloxane deposits on fiber surfaces. (Dilfi et al., 2018) indicates that silane treatment decreases water absorption, promoting adhesion between fiber and matrix by modifying hydrophilicity, ultimately improving compatibility with polymer matrices.

(E) Benzoylation Another common surface modification method for natural fibers to increase their compatibility with a hydrophobic polymer matrix is benzoylation. This process replaces hydrophilic groups with more hydrophobic benzoyl groups by reacting the hydroxyl (-OH) groups in the fiber's cellulose structure with benzoyl chloride (C_2H_2COCl). This chemical alteration strengthens the interfacial contact between the fiber and the matrix while decreasing the moisture absorption of natural fibers (Khalid et al., 2021b). Benzoyl chloride and the fiber's cellulose hydroxyl group modify the fiber, as seen in Equation 7 and Equation 8 (Sreekumar et al., 2008).

$$\text{Fiber-OH} + \text{NaOH} \rightarrow \text{Fiber-O}^-\text{Na}^+ + \text{H}_2\text{O} \quad \text{(Equation 7)}$$



(Equation 8)

Salih (2020) indicated that alkali serves as a pretreatment for benzoylation, removing wax, oil, and lignin. This process, combined with benzoyl chloride, diminishes hydrophilicity, thereby enhancing the interaction between fiber and matrix. Swain & Biswas (2017) recommended a treatment duration of 15 min, followed by 1 h of ethanol neutralization, washing with fresh water, and drying at 80°C for 6 h. It was found that post-benzoylation noted an improvement in mechanical properties, with the microfibril angle (MFA) decreasing from 23.4° in untreated fibers to 15.69° in treated fibers (Jena et al., 2024). This reduction allows for improved fibril alignment along the fiber axis, which results in a higher elastic modulus and lower elongation at break. Consequently, the treated fibers exhibit enhanced tensile strength and a notable increase in flexural strength in composites, estimated at 20-25%. Additionally, hydrophilicity reduction of 35–40% was observed, attributed to the reaction between cellulose and benzoyl chloride (Yadav & Gupta, 2019). In Izwan et al. (2021) experiment, it was observed that the thermal behavior of natural fiber composites treated with benzoylation and found a definite improvement following treatment. While the benzoylated composite showed an increase in degradation temperature up to about 360°C, the untreated composite showed cellulose and hemicellulose degradation about 340-350°C. Furthermore, after benzoylation, the char residue rose from around 16–18 weight percent in the untreated sample to about 20-22 weight percent, suggesting improved thermal stability and increased resistance to thermal breakdown.

(F) Combined treatment The effectiveness of jute fiber in composite applications depends on its surface properties, crystallinity, and compatibility with the polymer matrix. To overcome these limitations, researchers have applied combined chemical and physical treatment approaches. Effective evaluation and comparison of alkali, silane, plasma, and oxidative-based combined treatments was previous studied by several researches (Erdoğan et al., 2016; Gieparda et al., 2021; Rajesh & Prasad, 2014; Roy et al., 2020). Erdoğan et al. (2016) has provided a physicochemical comparison of alkali (AJ), alkali-silane (ASJ), and alkali-plasma (APJ) treatments using XRD, XPS and moisture content analysis. All treatments increased crystallinity (Table 2) due to the removal of non-cellulosic components.

Table 2: Crystallinity index of treated and untreated jute fiber

Treatment	Crystallinity (%)
Untreated	73
Alkali treated	83.8
Alkali-silane	85.9
Alkali-plasma treated	82.2

Crystallinity increased from 73% (untreated) to 83.8% (alkali), 85.9% (alkali-silane), and 82.2% (alkali-plasma), indicating that chemical treatment, particularly alkali–silane, increased cellulose chain orientation more effectively than others. However, the internal chemical composition changed significantly. Alkali treatment reduced the C/O ratio, which indicates hydrophobicity

(Table 3) from 6.6 to 3.0 due to the introduction of additional hydroxyl groups.

Table 3: C/O ratio of treated and untreated jute fiber

Treatment	C/O
Untreated	6.6
Alkali treated	3.0
Alkali-silane treated	5.7
Alkali-plasma treated	3.6

Alkali-plasma treatment showed only a slight increase in the C/O ratio (3.6), suggesting limited chemical modification with argon plasma. On the other hand, alkali–silane increased the C/O ratio to 5.7, indicating improved hydrophobicity through the formation of a polysiloxane layer on the fiber surface, which shielded polar sites. Moisture content results (Table 4) also aligned with these findings. Alkali-treated fibers showed the highest water absorption (18%), while alkali-silane treated fibers produced the lowest (4.7%), with alkali-plasma treated fibers showing in between values (5.6%).

Table 4: Moisture content of treated and untreated jute fiber

Treatment	**Moisture content (%)**
Untreated	7.0
Alkali treated	18
Alkali-silane treated	4.7
Alkali-plasma treated	5.6

This establishes alkali-silane treatment as the most effective for balancing structural enhancement and moisture resistance. Extending these findings to composite performance evaluated the effect of similar treatments, alkali, alkali-silane, and alkali-stearic acid, on jute fiber-reinforced natural rubber (NR) composites (Roy et al., 2020). This study highlights those untreated fibers lead to poor tensile properties due to incompatibility between hydrophilic fibers and hydrophobic matrix. Among treated fibers, alkali-silane again demonstrated superior performance, achieving the highest tensile strength (17.04±0.52 MPa), followed by alkali-stearic acid (15.91±0.44 MPa) and alkali (14.21±0.89 MPa). This confirms that silane coupling agents enhance interfacial adhesion by forming chemical bridges between fiber and matrix. While stearic acid improves surface hydrophobicity, its lack of strong chemical bonding limits its effectiveness compared to silane. Thus, Roy's results directly correlate improved surface chemistry with enhanced mechanical properties, reinforcing Erdogan's conclusions (Roy et al., 2020). In contrast, (Rajesh & Prasad, 2014) explored a different combined chemical approach using NaOH followed by hydrogen peroxide (H_2O_2) for jute/PLA composites. This treatment emphasizes fiber cleaning, partial delignification, and bleaching rather than hydrophobic modification. The optimal condition (10% NaOH + H_2O_2) resulted in a 7.5% increase in tensile strength and a substantial 125% increase in tensile modulus compared to untreated composites. These improvements are attributed to better fiber-matrix adhesion and reduced fiber pull-out due to cleaner and rougher fiber surfaces. However, unlike alkali-silane systems, this method does not significantly reduce moisture absorption or improve hydrophobicity, limiting its performance in moisture-sensitive applications.

Further insight into hybrid treatments is provided by (Gieparda et al., 2021) work on flax fibers, which examines the combined effects of silanization and plasma treatment on thermal, flammability, and hygroscopic properties. Plasma treatment alone resulted in moderate improvement in flammability (approx. 13% reduction in HRR_{max}), while silane treatments, particularly amino silane, achieved greater reductions (around 30%). In combined systems, the effectiveness depended on the silane type: aminosilane with plasma showed no additional benefit beyond silane alone, whereas vinyl silane combined with plasma exhibited a synergistic effect, reducing HRR_{max} by about 23%. Additionally, all treatments reduced hygroscopicity, with the lowest moisture absorption observed in silane–plasma combined systems. Compared to Erdogan's findings, this suggests that plasma treatment becomes significantly more effective when coupled with reactive chemical agents like silane, rather than when used with inert gases alone.

III. CONCLUSION

Jute fiber, primarily from the Indian subcontinent, contains over 30% noncellulosic portions, with a crystalline cellulosic structure and an elastic amorphous region. The key properties include microfibril angles and hydrophilicity, which pose challenges in composite applications due to bonding issues with hydrophobic matrices. Various surface treatments have been explored to enhance properties: alkali treatment improves adhesion but increases moisture absorption; plasma treatment enhances crystallinity and wettability but insufficiently reduces hydrophilicity; bleaching alters whiteness at a strength cost; and silane

treatment improves flexibility but decreases crystallinity. The combination of alkali and silane is preferred for better hydrophilicity reduction. Benzoylation also aids modification by lowering hydrophilicity and microfibril angles, yet achieves limited optimization on surface morphology. A synergistic approach combining multiple treatments yields the best results, as single treatments often fail to address all properties adequately. The effectiveness of surface treatment strategies hinges on the complementary nature of individual methods. Alkali treatment enhances crystallinity by eliminating amorphous fiber portions, maintaining hydrophilicity due to introduced external hydroxyl groups. However, plasma treatment shows limited hydrophilicity reduction due to its minimal surface modification capability. In contrast, the alkali-silane combination decreases surface polarity, boosting hydrophobicity and enhancing interfacial bonding between fiber and matrix. Additionally, silane-plasma synergy presents a promising alternative, improving moisture resistance, thermal properties, and flammability in fiber-reinforced composites. The combination of physical and chemical treatments is underexplored, highlighting a notable research gap for future optimization of composites.

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