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Exploring Composite Materials for Sustainable Environment through Jute Reinforced Starch-Based Innovations and Techniques

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Abstract

Composite materials emerge as a captivating avenue for bolstering sustainability across diverse applications by artfully integrating renewable resources, particularly through the creation of starch-based composites fortified with jute fibers via an injection molding technique. This process yields materials that are kind to the environment. By enhancing the bond at the interface between the jute fibers and the starch matrix, the mechanical characteristics, including strength and rigidity, saw noteworthy improvement. The jute strands underwent sodium hydroxide (NaOH) treatment for partial delignification, which fostered superior compatibility between the fiber and matrix. Additionally, a blocking reaction further amplified hydrogen bonding, culminating in exceptional mechanical performance. The findings underscore the viability of jute-starch composites as biodegradable options, boasting increased strength and rigidity, serving as practical, sustainable substitutes for conventional materials. This study underscores the significance of such composites in fostering eco-friendly solutions, particularly within the realms of green construction and packaging, while aligning with the larger objective of minimizing environmental footprints.

Keywords: Starch-based biopolymer, Jute strands, Alkali treatment, Reinforced biopolymer, Blocking reaction, Mechanical properties, Wettability.

1. Introduction

Composite materials, defined as entities constituted from an amalgamation of various fundamental components that demonstrate remarkably disparate physical or chemical properties, have garnered significant attention recently due to their potential to enhance sustainability. These materials combine the strengths of their components—typically a matrix and a reinforcement—resulting in products that are lighter, stronger, and more durable than traditional materials (Smith and Johnson 2023). As global challenges such as climate change and resource depletion intensify, the need for innovative materials that promote sustainability has never been more urgent. One of the primary advantages of composite materials is their ability to reduce weight without compromising strength. This characteristic is particularly valuable in industries like aerospace and automotive, where lighter materials contribute to greater fuel efficiency and lower emissions (Choi and Han 2023). For instance, using carbon fiber-reinforced polymers (CFRPs) in aircraft construction can lead to significant reductions in fuel consumption, thereby minimizing the carbon footprint of air travel (Correia and Carvalho 2020). As industries seek to align with stringent environmental regulations and sustainability goals, the adoption of lightweight composite materials becomes a strategic imperative.

The versatility of composite materials also allows for the integration of renewable resources. Bio-based composites, which utilize natural fibers such as hemp, jute, or flax as reinforcement, offer a sustainable alternative to conventional synthetic fibers (Naqvi et al., 2018). These bio-based composites not only reduce dependence on fossil fuels but also have the potential to sequester carbon dioxide during their growth cycle (Faruk et al., 2020). By harnessing agricultural waste and natural fibers, manufacturers can develop eco-friendly composites that support a circular economy while providing high-performance solutions across various applications (Joseph and Shivanand 2022).

In addition to their lightweight and renewable characteristics, composite materials exhibit enhanced durability and resistance to environmental factors (Arif et al., 2022). This resilience makes them suitable for applications in harsh environments, such as marine, construction, and automotive industries, where materials are often subjected to moisture, corrosion, and temperature fluctuations. The long lifespan of composites means less frequent replacement, contributing to reduced waste and resource consumption (Maiti et al., 2022). Thus, the incorporation of durable composite materials aligns with the principles of sustainability by promoting longevity and minimizing the ecological impact of manufacturing and disposal processes (Mohanty et al., 2023). Furthermore, the recyclability of composite materials presents a significant opportunity for enhancing sustainability. While traditional composites have faced challenges in recycling due to the difficulty of separating their components, advances in recycling technologies are paving the way for more sustainable end-of-life solutions (Pimenta and Pinho 2020). For example, chemical recycling processes can break down composite materials into their constituent fibers and resins, enabling their re-use in new products. This not only reduces landfill waste but also conserves resources by decreasing the demand for virgin materials (Raghavan and Liu 2021).

The development of smart composites, which incorporate sensors and actuators, adds another dimension to their sustainability profile. These materials can monitor their own condition and performance, providing valuable data that can inform maintenance and reduce the risk of failure.

By utilizing smart composites in infrastructure, for instance, we can enhance safety and efficiency while minimizing resource expenditure. This integration of technology into composite materials not only promotes sustainability but also supports the advancement of smart cities and resilient infrastructure (Rizvi and Gupta 2023). Despite the numerous advantages, challenges remain in the widespread adoption of composite materials for sustainable applications. Issues such as manufacturing costs, energy consumption, and the environmental impact of raw material extraction need to be addressed. Research and innovation in the production processes, including the use of green chemistry and energy-efficient methods, Figure 1 are critical to overcoming these barriers. Collaborative efforts among academia, industry, and government can foster the development of standards and regulations that support the sustainable production and use of composite materials (Wang and Yang 2022).

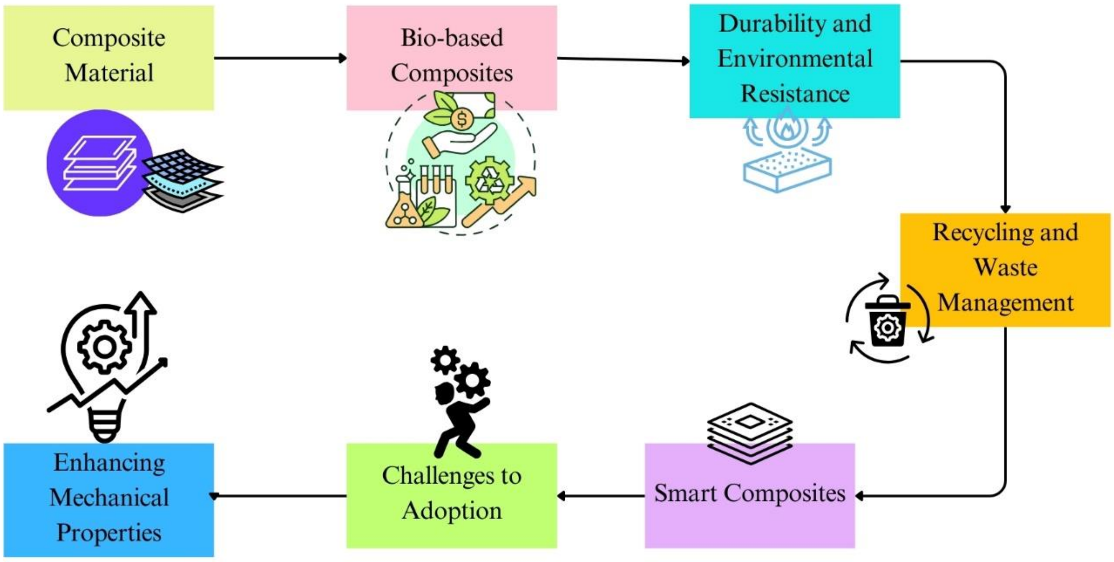

Figure 1. Composite Materials: Enhancing Sustainability through Innovation

The incorporation of non-biodegradable matrices and reinforcements within composite materials presents considerable challenges for effective waste management practices when these materials reach the end of their useful life cycle, causing significant concern for environmental sustainability. In light of the increasing stringency of governmental regulations and the rising tide of environmental consciousness among the global population, the emphasis has gradually transitioned towards the utilization of biodegradable polymers and fibers, (Xie and Wang 2022) which are instrumental in the creation of eco-friendly composites that align with ecological principles. Biocomposites, which are innovative materials consisting of a biodegradable polymer matrix that is ingeniously reinforced with natural fibers, are rapidly gaining prominence and attention within both scientific communities and industries due to their myriad environmental benefits.

Starch, recognized as one of the most extensively studied biopolymers in the field of material science, has undergone a remarkable transformation from its initial role as merely a filler in synthetic polymers to emerging as the primary polymer utilized in thermoplastics, particularly in applications where rapid degradation is not just beneficial but essential. However, (Zhong et al., 2009) despite the numerous advantages associated with biodegradable matrices, it is often necessary to incorporate reinforcement mechanisms to enhance their mechanical properties and overall performance in various applications. Plant fibers, which are harvested from renewable resources and therefore contribute to sustainability, offer significant environmental benefits; yet, they also encounter challenges such as high moisture absorption rates and suboptimal adhesion between the fiber and matrix, which can compromise the integrity of the composite.

To effectively enhance the properties of these composites, plant fibers can be subjected to either physical or chemical modifications, which serve to improve their compatibility and integration with polymer matrices, thereby optimizing performance outcomes. Through the enhancement of fiber-matrix interactions, these innovative biocomposites can achieve superior performance characteristics that can measure up to or even exceed those of traditional materials. Overall, composite materials possess immense potential for significantly advancing sustainability initiatives, providing a viable pathway towards reducing environmental impact and conserving precious resources across an array of industries and applications, ultimately shaping a more sustainable future for generations to come.

2. Experimental

2.1. Materials

Jute fibers, sourced from the esteemed Celulosa de Levante S.A., located in Tortosa, Spain, were provided in their initial form with varied lengths ranging from an impressive 10 to a full 20 centimeters, showcasing the natural beauty and versatility of this remarkable plant material. To facilitate the alkali treatment of these jute strands, sodium hydroxide pellets, acquired from the renowned Merck corporation situated in Darmstadt, Germany, were employed, ensuring that the fibers underwent a thorough and effective transformation process. In order to effectively block the hydroxyl groups adorning the surface of the jute fibers, phenyl isocyanate, known for its exceptional purity and obtained from Fluka in Buchs, Switzerland, served as a vital blocking agent, thus amplifying the chemical attributes of the fibers. The alteration of the jute fibers was further propelled by dibutyltin dilaureate (DBTL), which possessed an admirable purity of 95% and was acquired sourced from the esteemed Sigma-Aldrich Chemie, nestled in the picturesque town of Steinheim, Germany, the compound plays a pivotal role in facilitating the intricate process of surface modification reactions, which are crucial for various applications in chemical research and development. Meanwhile, carbon tetrachloride, which is undeniably another integral component of this multifaceted and complex chemical procedure, was procured from the reputable supplier Panreac, located in the charming area of Castellar del Vallès, Barcelona, known for its rich history in chemical manufacturing.

Together, these substances intertwine to create a tapestry of chemical interactions that not only enhance the desired properties of materials but also propel the boundaries of scientific innovation into uncharted territories, Spain, and was chosen for its excellent solvent properties during the modification reaction, ensuring that the entire process proceeded smoothly. Prior to its application in the reaction, this carbon tetrachloride was meticulously dried using molecular sieves, a process that required at least 12 hours of careful preparation to ensure optimal results.

In the creation of the composite material, a remarkable biopolymer derived from starch, which is thoughtfully provided by the esteemed company Ribawood, S.A, whose headquarters are located in the picturesque city of Zaragoza, Spain, has been creatively employed as the essential polymer matrix that serves as a foundational component in various innovative applications and projects, providing the necessary structural integrity and functionality to the final product. This innovative starch-based biopolymer was characterized by a specific gravity that contributed to its efficacy, alongside a melt flow index that was meticulously measured under specified conditions, particularly at a load of 5 kg, ensuring the material's performance met the required standards.

2.2. Washing and alkali treatments

In an intricate procedure, the fibers of jute were skillfully trimmed to an exact nominal length of 10 mm, utilizing the keen edges of a specialized mill crafted for this specific task. After this preparatory step, the jute fibers were subjected to an extensive washing process, where they were submerged in tap water for a full hour, followed by a rinse with distilled water, and ultimately, they were carefully dried in an oven at a precisely regulated temperature for three hours. Once the washing was accomplished and the fibers properly dried, a chosen segment of these jute strands was set aside, intended for use as essential reinforcement material in the groundbreaking formulation of starch-based composites. Simultaneously, another portion of the jute strands underwent an alkali treatment, as noted in earlier research.

To achieve this, the jute fibers were placed into a reaction vessel, where a precisely measured solution of sodium hydroxide was introduced to the fibers, ensuring they were completely coated. The resulting mixture was then kept at room temperature for three hours, during which it was constantly stirred to facilitate a uniform reaction. Once the allotted time had passed, the reaction medium was carefully filtered to isolate the treated jute strands, which were then thoroughly rinsed with distilled water until neutrality was achieved, ensuring that all residual alkali was removed. Finally, the alkali-treated jute strands underwent a drying process in an oven at a controlled temperature for another three hours, after which they were stored for future use as reinforcement in the preparation of the starch-based composites, thus completing an intricate series of preparations and treatments that enhance the properties of the final product shown in figure 2.

Figure 2 alkali treatment

2.3. Blocking reaction

A chemical alteration utilizing mono-phenyl isocyanate was executed on jute fibers to obstruct their hydroxyl (OH) functionalities, thereby boosting their characteristics. The procedure comprised dissolving phenyl isocyanate and dibutyltin laurate (DBTL) in a solvent and subjecting the jute fibers to a nitrogen atmosphere for 72 hours. Following the treatment, the fibers were washed and air-dried to eliminate any residues. This technique enhanced the fibers' capabilities, underscoring the promise of chemical alterations to improve natural fibers for diverse applications in materials science.

2.5. Polarity measurements

The fiber suspension's the assessment of the polarity of the substance in question was meticulously conducted by means of a sophisticated technique known as colloidal titration, during which the unique properties of methylglycolchitosan (MGCh) were skillfully employed as the primary agent or medium for this intricate evaluation process, thereby allowing for a nuanced understanding of the interactions at play positively charged polymer and toluidine blue as the visual indicator. This technique, pioneered by Terayama in 1952, quantifies the cationic demand or the volume of cationic polymer that bonds with the fiber's surface. Following the introduction of a surplus of MGCh to the suspension, the blend was vigorously mixed and then subjected to colloidal titration to ascertain the polarity traits of the fiber.

2.6. Preparation of starch-based composites

A fusion of starch-based biopolymer composites enriched with hemp fibers was crafted utilizing a heated roll mixer for a duration of 10 minutes. Mixtures containing 10%, 20%, and diverse reinforcement levels were transformed into granules through a blade mill, subsequently shaped in an injection-molding apparatus. The machine parameters were fine-tuned to ensure a sleek surface finish while maintaining the integrity of the fiber's aspect ratio. The injection specifications encompassed temperatures, injection durations, and screw velocity Shown in figure 3. The steel mold conformed to ASTM D3641 criteria, and the samples underwent conditioning in accordance with ASTM D618 guidelines. A total of ten specimens from each composite blend were subjected to performance testing.

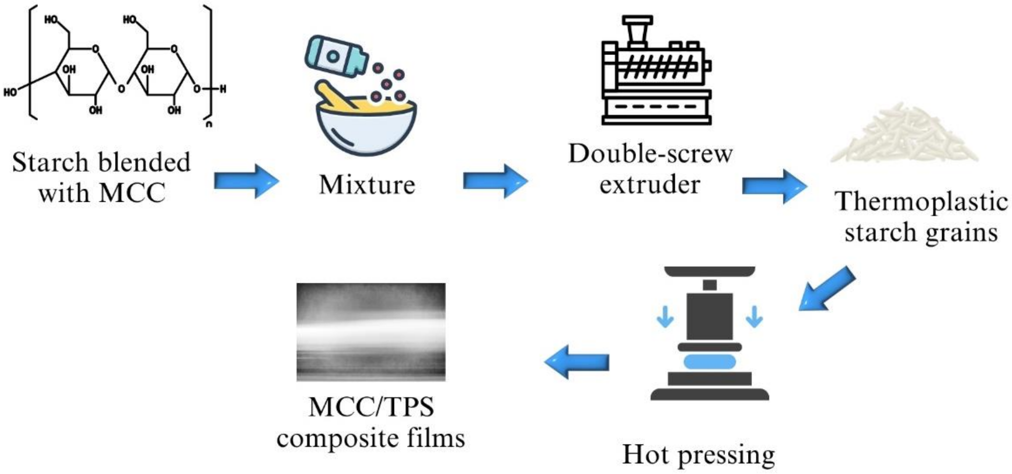

Figure 3 Preparation of starch-based composites

2.9. Optical microscopy

A sophisticated Leica DMRXA optical microscope was meticulously utilized to scrutinize and analyze the intricate dimensions of the fibers after they underwent a comprehensive processing procedure. In order to accurately assess the varying sizes of these fibers, the composite materials were thoughtfully immersed in xylene for an extensive period of three days, and subsequently, the fibers were carefully dried under vacuum conditions to ensure optimal results. The thorough evaluation of the fiber dimensions was carried out with precision through the use of optical microscopy, which was seamlessly integrated with the advanced Sigma Scan Pro image analysis software, allowing for detailed and insightful measurements. This combination of innovative technology and methodical techniques provided a robust framework for understanding the characteristics of the fibers in great detail.

2.10. Moisture absorption

The meticulous evaluation concerning the capacity of untreated jute strand and starch composites to absorb moisture involved carefully positioning the samples inside a hermetically sealed glass container, which was expertly maintained at a stable temperature of precisely 20 degrees Celsius while simultaneously ensuring that the relative humidity was kept at an impressive level of 98%. Each day, the samples were delicately weighed, with this process continuing until the moment when a consistent weight was achieved, signifying that the materials had reached a state of complete moisture saturation, thus indicating the thoroughness of the absorption process. The percentage increase in weight that was methodically recorded served a crucial purpose, as it was employed to assess the rate at which moisture was absorbed, offering invaluable insights and a deeper understanding into how these particular materials perform when subjected to humid environmental conditions. Ultimately, this comprehensive analysis not only elucidates the properties of the composites but also lays the groundwork for future research and potential applications in areas where moisture management is of paramount importance.

3. Results and discussion

Table 1 provides a detailed illustration of the mechanical characteristics of starch-based biopolymer composites that have been fortified with various proportions of jute strands, which have undergone different treatment processes, including being untreated, subjected to alkali treatment, or modified through the application of Ph-NCO. It is noteworthy that the tensile strength of these composites exhibited a remarkable and substantial increase as the percentage of jute content was raised, revealing enhancements of 35%, 54%, and an impressive 68% for the incorporation of 10%, 20%, and 30% (w/w) jute strands, respectively, which underscores the direct relationship between jute content and tensile strength. Furthermore, the improvements in flexural strength were even more striking and pronounced, showcasing increases of 48%, 61%, and a staggering 89%, thus highlighting the potential of jute as a reinforcing material in these composites.

The remarkable enhancements in mechanical properties can be attributed to the highly effective adhesion between the fibers and the matrix, which is influenced by several critical factors, including the mechanical interlocking or anchoring of the fibers within the matrix, the presence of electrostatic attractions between the components, and the formation of hydrogen bonds that contribute to the overall strength. The unique and irregular topography, coupled with the high porosity of the jute strands, plays a crucial role in facilitating superior interactions with the matrix, thereby significantly enhancing wettability and adhesion, which are essential for the integrity of the composite. Even though there was a notable reduction in fiber length during processing—from an original length of 10 mm down to approximately 0.55 mm—the aspect ratio of the jute strands remarkably remained above 30, which is a crucial factor contributing positively to the mechanical performance of the composites. In addition to these findings, it is essential to highlight that the Young's modulus of the composites also experienced a significant increase, with enhancements of an astounding 80%, 180%, and a remarkable 310% occurring as the percentage of jute reinforcement was elevated. This increase in stiffness is intricately linked to both the level of reinforcement provided by the jute and its effective dispersion throughout the polymer matrix, which optimizes the mechanical properties. However, it is also imperative to acknowledge that the quality of the interface between the fibers and the matrix plays a vital role in determining the effectiveness of this reinforcement, emphasizing the complex interplay between material properties in achieving optimal composite performance.

Table 1: Mechanical Properties of Starch-Based Biopolymer, Untreated Jute Fiber/Starch Composites, NaOH-Treated Jute Fiber/Starch Composites, and Chemically Treated Jute Fiber/Starch Composites.

Reinforcement (%)	**Tensile Strength (MPa)**	**Young's Modulus (MPa)**	**Elongation (%)**	**Flexural Strength (MPa)**	**Impact (kJ/m²)**
Untreated Jute Fibers					
0	14.5 ± 0.60	620 ± 30	21.0 ± 1.5	20.0 ± 1.0	79.0 ± 3.0

10	18.2 ± 0.55	1120 ± 15	8.0 ± 0.6	29.0 ± 1.1	14.0 ± 0.8
20	21.0 ± 0.50	1750 ± 20	3.5 ± 0.3	33.5 ± 0.7	12.0 ± 0.7
30	24.0 ± 0.40	2500 ± 25	1.5 ± 0.2	38.0 ± 1.2	9.0 ± 0.6
NaOH Treated Jute Fibers					
10	22.0 ± 0.70	1150 ± 18	7.5 ± 0.5	31.0 ± 1.5	17.0 ± 1.5
20	25.5 ± 0.55	1700 ± 30	3.0 ± 0.3	36.0 ± 0.9	14.0 ± 1.0
30	28.0 ± 0.60	2550 ± 20	2.2 ± 0.2	42.0 ± 1.0	12.0 ± 0.8
Ph-NCO Treated Jute Fibers					
30	12.0 ± 0.50	2000 ± 15	1.0 ± 0.1	22.0 ± 0.5	9.0 ± 0.5

The Table 1, mechanical characteristics of starch-based biopolymer composites are significantly shaped and influenced by various factors, including the specific type of reinforcement utilized and the percentage of that reinforcement incorporated into the composite, as well as the extent to which this reinforcement is evenly dispersed throughout the polymer matrix, all of which are essential elements in the quest to enhance the rigidity and overall performance of these composite materials. The numerical values showcased in the accompanying table represent the average values obtained from the experiments, with the notation ± indicating the standard deviation, thereby providing a clearer understanding of the variability present in the data collected.

By applying the established rule of mixtures, one can effectively ascertain the compatibility factor, which can be mathematically articulated through the following equation (1), serving as a fundamental tool in the analysis of composite material behavior.

$$Compatibility\ Factor = Ef - Em/Ec - Em$$

where Ec is the modulus of the composite material, Em denotes the modulus of the matrix, and Ef represents the modulus of the fiber. This equation helps assess how well the reinforcement interacts with the matrix, ultimately affecting the overall mechanical performance of the composite.

One more significant factor that warrants careful consideration when delving into the intriguing realm of composite materials derived from starch-based biopolymers, specifically focusing on the unique combination of starch and jute, is undoubtedly the critical aspect of moisture absorption. As illustrated in Figure 4, which serves as a visual representation, one can observe the gradual progression of moisture absorption in untreated jute strand/starch composites when subjected to varying conditions at the intervals of 10 and 20, alongside the corresponding percentage of reinforcement.

After a prolonged period of 72 days, the amount of humidity that was absorbed remained remarkably low, suggesting a strong resistance to moisture infiltration within these composites. Furthermore, it is noteworthy to mention that the increment in the percentage of reinforcement did not significantly impact or alter the overall moisture absorption capacity in any substantial manner, indicating a level of durability and stability in the material's performance. The Table 2, experimental values gathered from these observations provided a wealth of data that clearly demonstrated the resilience of these composites against moisture, thus highlighting their potential applications in various industries.

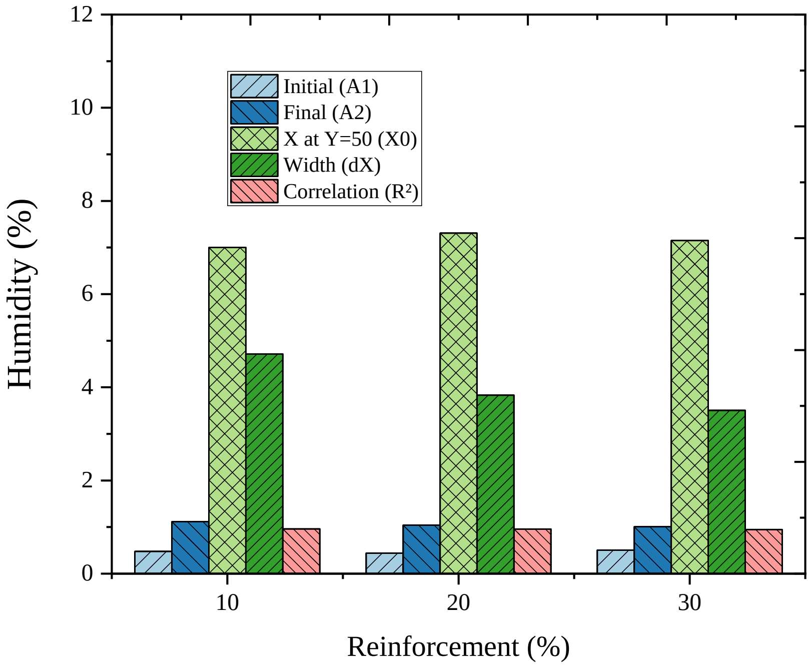

Figure 4 Moisture Absorption Parameters of Untreated Jute Strand/Starch Composites at 10%, 20%, and 30% Reinforcement Levels: Boltzmann Curve Analysis

Table 2: µ Equiv. of Cationic Polymer Absorption per Gram of Substrate for Composite Constituents

Material	**Crude Jute Strands**	**NaOH Treated Jute Strands**	**Ph-NCO Modified Jute Strands**	**Starch-Based Biopolymer**

Polarity (µ Equiv. MGCh g^{-1})	12.16 ± 0.01	19.18 ± 0.01	6.75 ± 0.01	13.26 ± 0.01

The fusion of lignin and diverse elements found within jute fibers profoundly impacted the mechanical traits of the composites. As illustrated in Table 1, mechanical evaluations indicated a striking decline in the measurements pertaining to the tensile strength as well as the flexural strength of the composites that have undergone modification with jute fibers, which were astonishingly documented to exhibit a reduction that is precisely 48% lower than their original values, reveal significant insights into the performance characteristics of these innovative materials when juxtaposed with their untreated equivalents. These results underscore the significant influence of increased hydrogen bonding at the juncture in the intricate interplay between the fibrous strands and the surrounding matrix, there existed a delicate balance that ultimately transformed the composite's overall rigidity in remarkable ways. Consequently, this intricate relationship led to a significant modification in the Young's modulus of the jute fiber composites that had undergone treatment, showcasing the fascinating dynamics of material science at work. The changes observed were not merely numerical but represented a profound evolution in the performance characteristics of these composites, illustrating the potential for innovation in sustainable materials engineering found to be 0.8 times that of the untreated samples.

4. Conclusions

Composite materials are crucial in advancing sustainability by merging the advantages of lightweight design, exceptional strength, and adaptability while reducing ecological harm. The evolution of bio-based composites sourced from renewable materials not only boosts resource efficiency but also aids in diminishing waste through recycling and repurposing efforts. Additionally, incorporating sustainable methods in the creation and application of composite materials can greatly reduce carbon emissions and support circular economy concepts. As exploration continues to innovate in this domain, the embrace of composite materials across diverse industries—from construction to automotive—will be vital for realizing a greener and more sustainable future. The intricate mechanical characteristics of composite materials that are skillfully crafted from biopolymers derived from starch and artfully reinforced with the natural jute fibers were meticulously investigated, with a particular emphasis placed on analyzing how the varying polar attributes of the jute strands could potentially influence the overall performance of these composites.

The findings from this comprehensive study revealed that both the tensile and flexural strength of the materials experienced a remarkable enhancement when a higher proportion of unmodified jute strands was incorporated, a phenomenon that can be largely attributed to the effective mechanical interlocking that takes place, along with the improved hydrogen bonding that occurs at the critical interface between the fiber and the matrix. Furthermore, it was observed that the Young's modulus of the composites, which is a measure of their stiffness, increased significantly as the percentage of reinforcement from the jute strands was elevated, even in the face of a low compatibility factor that was suggested by the Mixture Rule. Nevertheless, it is noteworthy that as the stiffness of these composites saw an upward trend, there was a concurrent decline in both the elongation and the impact energy, indicating a complex interplay between strength and flexibility. In summary, the research highlights the delicate balance that must be achieved when designing composite materials that utilize natural fibers, as one must consider the trade-offs between enhanced mechanical properties and the inherent ductility of the resulting material. This exploration into the mechanical properties of these innovative composites not only opens up new avenues for their application but also poses intriguing questions for future research in the field of sustainable materials engineering.

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