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Research Article

# Analysis of the Effects of Fiber Loading on the Mechanical Behavior of Jute Reinforced Thermoplastic Composites

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## Abstract

Natural fiber-reinforced composites are becoming a growing trend because of their affordability, sustainability, abundant natural source, and minimal environmental effect. It has also shown to be an effective replacement of synthetic fiber, particularly in the transportation and construction sectors as ceiling, paneling, partition etc. In this study the jute fiber (Hessian Cloth) reinforced (10% to 50% fiber content by weight) Polypropylene (PP) and Polyethylene (PE) composite were made by compression molding technique to understand the effect of fiber loading on mechanical properties of two different thermoplastic composite materials. For jute fabric-reinforced thermoplastic composites, it was discovered that with 30 % fiber loading with PP and PE yielded the best results. It was found that the mechanical properties of the composites enhanced significantly with 30 % fiber content with PP and PE thermoplastic matrixes in contrast to 10% and 20% fiber content composites. However, increasing the fiber content over 30%, dramatically decrease the mechanical properties of the composite samples. The relationship between Tensile Strength (TS), Bending Strength (BS), Impact Strength (IS) and Tensile Modulus (TM), Bending Modulus (BM) was examined, along with water resistance properties for both composites. Additionally, the jute-reinforced polypropylene (PP) composite showed superior mechanical capabilities compared to the jute-polyethylene (PE) composite. This suggests that it could be a suitable replacement for the toy manufacturing, home or garden furniture, automotive and interior construction industries in the future.

## Keywords

Composite Material, Jute Fiber, Polyethylene, Polypropylene, Mechanical Properties, Water Absorption

## 1. Introduction

For thousands of years, composite materials have been used for a wide range of applications. Until the plastics were developed, composite materials were made of natural fibers and natural resins. Ancient Greeks and Romans reinforced concrete using hemp fibers, while Egyptians used straw to reinforce mud bricks [1]. Now a days, natural fiber-reinforced polypropylene and polyethylene composites are finding more and more uses in engineering products like the bodies of electronic appliances, transportation vehicles, building materials, the automotive industry, and many more due to their better performance, higher ultimate strain and good impact resistance. Natural fibers' primary benefits are their low cost and biodegradability, despite the fact that they are not as strong as synthetic fibers. Natural fiber's shortcomings, including its wettability, incompatibility with various polymeric matrixes, and excessive moisture absorption, have hindered its full replacement with synthetic fiber [2, 3].

Jute is the most practical, affordable, and widely accessible

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natural fiber available in Bangladesh. It can be formed into a range of complex and flat shapes by taking advantage of its appealing reinforcing properties. The three main components of jute are a-cellulose, lignin and hemicellulose. It also contains trace amounts of inorganic and nitrogenous substances like lipids and waxes, xanthophylls and beta-carotene [4, 5]. Jute fiber mostly consists of a hydrophilic gluten polymer, which is made up of a linear chain of 1,4-b-a hydro glucose units. Water absorption of jute fiber can be decreased by forming hydrogen bonds between parallel chains by the crystalline regions of hydroxyl groups. It is generally true that jute's mechanical and physical properties are very variable and depend on a variety of factors, including its physical state, chemical composition, growth conditions, and geographic origin. They are also influenced by the processing methods used. Compression molding is a popular manufacturing technique used to prepare composite samples, polyethylene and polypropylene sheets. Jute fiber can be combined with polymer matrix polyethylene or polypropylene in this manufacturing process to produce durable products with improved mechanical qualities. In this process, a mold cavity is filled with a polymer grain matrix and jute fiber. After that, the material is forced into the mold by pressure and heat, taking on the shape of the mold. Jute fiber can be impregnated into the polymer matrix because of this temperature and pressure combination, guaranteeing a consistent distribution of the matrix throughout the material [6, 7]. Due to a number of drawbacks, jute is also inappropriate for optimum reinforcement including poor wettability, poor fiber-matrix adhesion, intrinsic polarity because of the presence of hydroxyl and carboxyl groups in their structure, and low moisture resistance [8]. In an attempt to address this problem, a variety of techniques, such as chemical and physical treatments (gamma radiation, nanoparticles, etc.), alter the surface energy and structure of the fibers [9]. Composite materials reinforced with jute fibers are the subject of wide research and scientists have demonstrated the potential of jute fabrics as reinforcing materials [10-12]. Degradable jute reinforced polymer matrix composites have been created by Khan et al. [13] by combining silicon and vinyl monomers.

The material that gives the composite component its form, stabilizes the reinforcing fibers, and controls the surface quality is called the matrix. The majority of degradative processes that eventually cause a structure to fail, including delamination, fracture propagation, water absorption, impact damage, thermal creep, and chemical assault, are inhibited by the composite's resistance to these qualities. Furthermore, the matrix of composite materials maintains the fibers' orientation and position so that they can bear the intended loads and distribute them among the fibers fairly. This prevents cracks from spreading because of the plastic flow at the points of cracks. Thermoplastic polymer resins are widely used and, in general, less expensive to fabricate than thermosets or elastomers. Thermoplastic composite materials offer two main benefits. First off, as compared to thermoset resins, many thermoplastic resins have higher impact strength and toughness. The capacity of thermoplastic composites to be readily recycled and reformed is another important advantage. This property is highly valued in the present commercial sector [14]. Jute fibers have also been reported to be utilized as reinforcement in a number of thermoplastics, including polyethylene (PE) and polypropylene (PP), as well as thermo-sets, such as epoxy resin and unsaturated polyester [15, 16]. Compared to branching polymers, the synthetic polymer PE is stiffer, tougher, and very chemically inert. They have a higher softening temperature (135 °C) and a higher tensile strength. PE has a specific gravity of 0.92–0.98 and excellent moisture resistance properties. Compared to PE, PP has a comparatively high melting temperature (170–180 C), stiffness, strength, and hardness due to its high crystalline structure. PP is an amorphous thermoplastic polymer that finds extensive application in engineering thermoplastics due to its several essential and beneficial characteristics, including minimal moisture pickup, transparency, high mechanical strength, high heat distortion temperature, and good dielectric qualities. Additionally, PP works well for mixing, filling, and strengthening [12, 17, 18].

The creation of the finished composite products as engineering materials into the correct shape with no flaws depends critically on the choice of an appropriate manufacturing technique to create the structure. The overall shape, size, and intended features of the composites, as well as the cost of manufacturing, the rate of production, and the characteristics of the raw materials, are all taken into account during the preliminary evaluation to determine the best manufacturing procedure [19]. The development of better processing methods is one of the main reasons that NFRCs have advanced. High-pressure impregnation and hot press molding, for instance, have produced composites with improved fiber-matrix adhesion and more uniform fiber distributions. Furthermore, the development of composites with enhanced mechanical properties has been made possible by the application of sophisticated polymer processing methods such melt mixing [20]. High-quality composites may be produced in compression molding by carefully regulating a number of crucial process variables, including pressure, holding time, viscosity, and curing temperature, while taking a variety of fiber and matrix into consideration. For the intended composite pieces, these characteristics must be carefully chosen. It is important to pay close attention to temperature in particular since there is often a little gap between the temperature at which a certain matrix may be processed and the temperature at which fiber deterioration will begin [21].

The purpose of this work is to investigate the fiber loading effects on mechanical characteristics of jute fiber (hessian fabric) composites made of PP and PE reinforced using the compression molding process. Here, the behavior of the resultant composites' water uptake was also investigated for applications that are more commonly found in the transportation (autos, train carriages, etc.), building and construction (partition boards, ceiling panelling, etc.), and consumer products industries.

## 2. Materials

We collected Hessian cloth (commercial quality, bleached Tossa Jute) from Bangladesh Atomic Energy Commission, Dhaka, Bangladesh. We bought polypropylene and polyethylene from Borouge Company in UAE, showed in Figure 1.

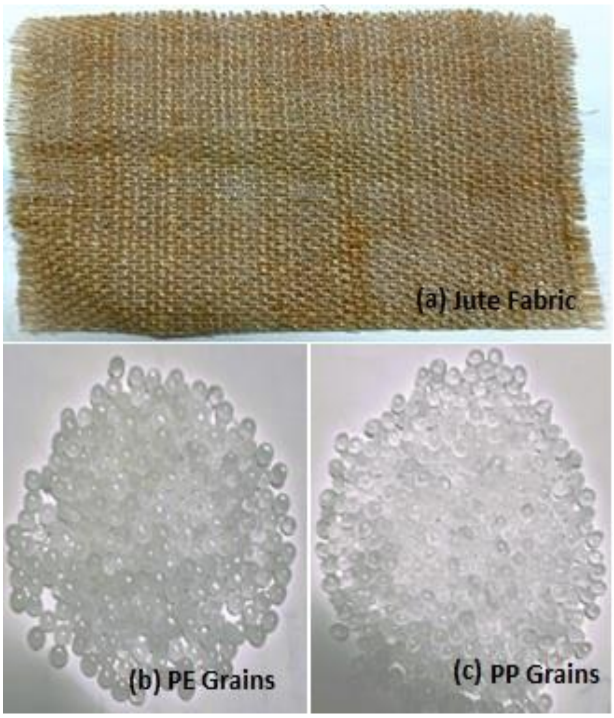


*Figure 1. (a) Jute hessian cloth (b) Polyethylene (PE) grain (c) Polypropylene (PP) grain.*

## 3. Composites Preparation

For jute-reinforced polyethylene and polypropylene sheets, compression molding technique ensures the creation of sheets with consistent thickness and density. The resulting sheets exhibit improved tensile strength, impact resistance, and durability compared to nonreinforced sheets. Using a Carver Laboratory (USA) press set at 140 ℃ and 180 ℃ for PE and PP polymer granules respectively to heat pressed to create thin sheets with a thickness of 0.25–0.30 mm on an individual basis. The polymer matrixes sheets were divided into tiny pieces, measuring 15 cm by 12 cm, and stored in desiccators until the composite was constructed. Jute materials were chopped into tiny pieces of 15 by 12 cm after being dried for one hour at 105 ℃ in an oven to eliminate moisture. The composites were created by sandwiching three layers of jute cloth between four layers of pre-weighted polymer matrix sheets (PE and PP) showed in Figure 2, then pressing it between two steel plates or mold at 140 ℃ and 180 ℃ respectively for five minutes while applying 5 tons of pressure. After that, the composite material comprising the steel sheets was cut to the required size and allowed to cool to room temperature in a different press (Carver, USA) showed in Figure 3 and Figure 4. Following the compression molding process, composite samples are prepared by cutting and shaping the sheets into standardized specimens (15 by 2 cm) for mechanical testing. These samples then undergo a range of tests, including tensile strength, bending strength, impact strength, and water uptake, to assess their mechanical and physical properties. The controlled conditions during compression molding contribute to the reliability and consistency of these mechanical tests.

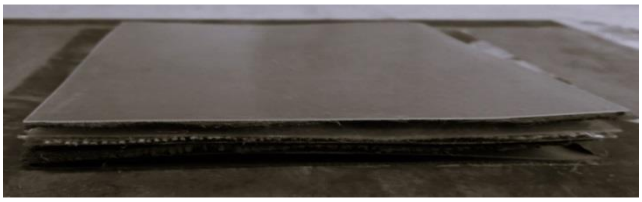

*Figure 2. Three-layer jute cloth and four-layer matrix sandwich setup of composite.*

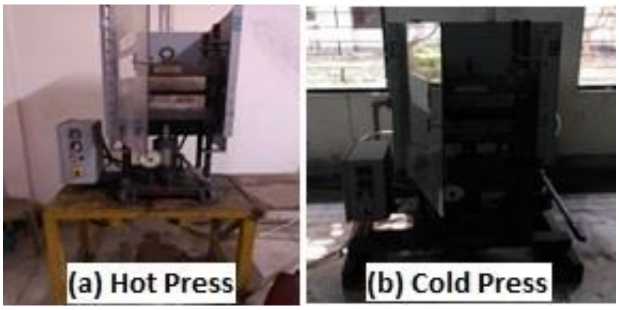


*Figure 3. Carver Laboratory (USA) machine (a) Hot press (b) Cold press.*

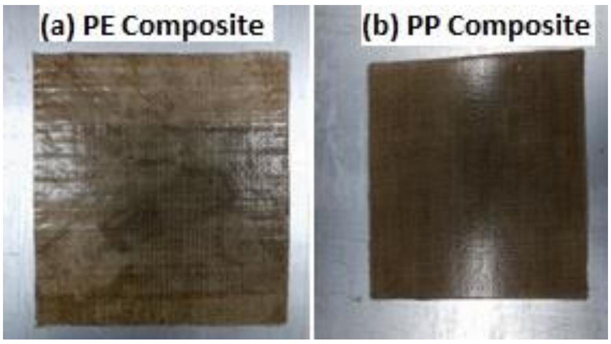


*Figure 4. Jute reinforced (a) Polyethylene (PE) composite and, (b) Polypropylene (PP) composite.*

## 4. Mechanical Tests

Using a VICTOR universal testing equipment showed in

Figure 5, with a 20 mm gauze length, the mechanical properties of the composites, including tensile strength (TS), bending strength (BS), tensile modulus (TM), and bending modulus (BM), were measured in accordance with DIN 53455 and DIN 53452 standard methods. The impact strength (IS) was measured in the flat-wise, un-notched mode using an impact tester (MT-3016) in accordance with DIN EN IS0 179 standard. Each and every result was calculated using the average of 6 samples.

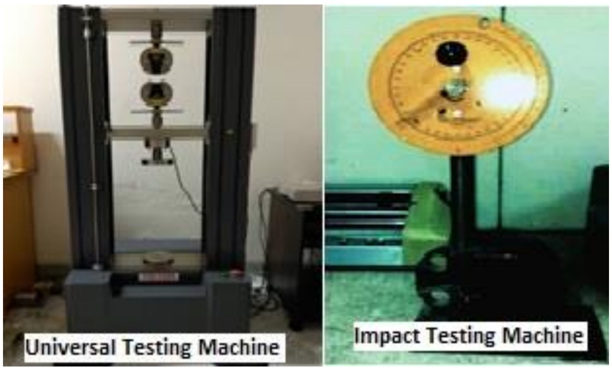


***Figure 5.*** *(a) VICTOR universal testing machine, (b) Impact tester machine (MT-3016).*

The ability of the PE and PP composites to absorb water was determined by soaking the samples—each composite having a length of approximately 3 cm-in water in a glass beaker at 20 degrees Celsius and 64% humidity for varying lengths of time, up to 50 hours. The weight that the submerged samples gained was used to calculate the sample's water uptake.

# 5. Results and Discussion

## 5.1. Mechanical Properties of the Composites

A material is categorized and differentiated from others based on its mechanical properties. How a substance responds to an applied force is determined by its mechanical properties. Tensile, flexural, impact, and water absorption tests are frequently used to evaluate the mechanical characteristics of natural fiber composites [22]. In an effort to increase mechanical qualities and decrease moisture absorption, researchers are working to create novel techniques for treating jute fibers in reinforced composites. In order to test the mechanical properties of jute-bamboo fiber-based polymer composites for use in skateboards and safety helmets, the ideal amount of jute and bamboo fibers could be added to increase the composite's tensile properties up to 49.89 MPa [23]. A maximum bending strength of 89.12 MPa was demonstrated by a hybrid jute and coir fiber composite with jute fiber orientation of 45 °/45 ° and coir fiber orientation of 0 °/90 ° [24].

Two types of composites based on PE and PP thermoplastic matrixes reinforced with jute fibers were prepared, and their mechanical properties were assessed shown in Table 1. and Table 2, respectively. The composites were kept between 10% to 50% fiber loading by weight of jute. Across all jute content levels, the tensile strength of PE composites is substantially less than that of PP composites. For both composites, 30% of jute content produces the best tensile strength. When compared to PE, PP composites have a higher tensile strength that of 32.55 MPa at 30% of jute content loading. For applications requiring better tensile qualities, PP is the preferred material. PE composites' bending strength exhibits an improvement with increasing jute content, following a similar trend to that of their tensile strength. 30% is the ideal amount of jute. The fiber serves as the primary load-bearing component in polymer composites because its strength and stiffness are significantly greater than those of the matrix material. Conversely, the matrix acts as a load distributor by uniformly distributing the delivered force across the fiber. In order to create an efficient load transfer and enhance the mechanical properties of polymer composites, the matrix must securely hold a sufficient amount of fiber [25].

### 5.1.1. Tensile Strength (TS) and Bending Strength (BS)

The PE and PP composite's TS and BS are displayed in Figure 6 in proportion to the weight percentage (wt%) of jute fiber content. In the illustration, 10% meant that the composite's matrix content was 90% and its fiber content was 10%, while 50% meant that the composite's weight was 50% matrix and 50% fiber. The TS and BS of the PE composites reinforced with jute fiber were determined to be 13.32, 19.22, 21.90, 16.78, 14.95 MPa and 16.65, 25.37, 29.13, 22.65, 19.44 MPa from 10 to 50% of fiber content, respectively. The fiber-matrix interfaces and jute fiber flaws, which significantly affected the composite's tensile strength, can also be used as justification for the low tensile strength. The strength of the composite is greatly reduced by the voids and lack of bonding with the fiber-matrix interface [26].

The highest mechanical characteristics in the figure are shown by 30% of fiber content for jute reinforced PP based composite. However, the PP-based composite's with fiber content of 10% to 50%, the TS and BS increased to 32.55 and 42.64 MPa for 30% of jute fiber content, respectively. After that, TS and BS decrease to 27.44 and 10.55 MPa for 50% matrix content, respectively. This study clearly shows that, in comparison to jute fiber reinforced PE composites, PP based composites had significantly higher values of TS and BS and both composites are showing highest mechanical properties with 30% of jute fiber content. Studies on natural fiber composites' bending characteristics indicate that BS is related to both fiber length and content. Longer fibers can bear loads more effectively because they have more space for stress transmission; but, if the fibers are too long, they may tangle during combining and result in poor fiber dispersion, which can reduce the overall effectiveness of composites [6]. The TS of the PP matrix composite, which was composed of 10% to 50% of jute fiber content is 67.10%, 30.62%, 48.61%, 71.30%, 83.51% higher than PE based composites, respectively. On the other hand, the BS and TS of the PP matrix composite, which was composed of 30% of jute fiber content is 46.22% and 18.62% higher than that of PP matrix composite, which was composed of 10% and 50% of jute fiber content, respectively.

*Table 1. Mechanical properties of (10 to 50) % jute reinforced PE composite.*

| Properties | Units | PE (10%) | PE (20%) | PE (30%) | PE (40%) | PE (50%) |
|---|---|---|---|---|---|---|
| TS | MPa | 13.32 | 19.22 | 21.9 | 16.78 | 14.95 |
| BS | MPa | 16.65 | 25.37 | 29.13 | 22.65 | 19.44 |
| TM | GPa | 0.11 | 0.54 | 0.74 | 0.45 | 0.21 |
| BM | GPa | 0.25 | 0.38 | 0.44 | 0.34 | 0.29 |
| IS | kj/m2 | 14.64 | 16.53 | 19.47 | 15.74 | 13.66 |

*Table 2. Mechanical properties of (10 to 50) % jute reinforced PP composite.*

| Properties | Units | PP (10%) | PP (20%) | PP (30%) | PP (40%) | PP (50%) |
|---|---|---|---|---|---|---|
| TS | MPa | 22.26 | 25.10 | 32.55 | 28.74 | 27.44 |
| BS | MPa | 29.16 | 32.88 | 42.64 | 37.65 | 35.95 |
| TM | GPa | 0.53 | 0.46 | 0.87 | 0.40 | 0.30 |
| BM | GPa | 0.44 | 0.49 | 0.64 | 0.56 | 0.54 |
| IS | kj/m2 | 9.17 | 11.92 | 13.37 | 12.29 | 10.55 |

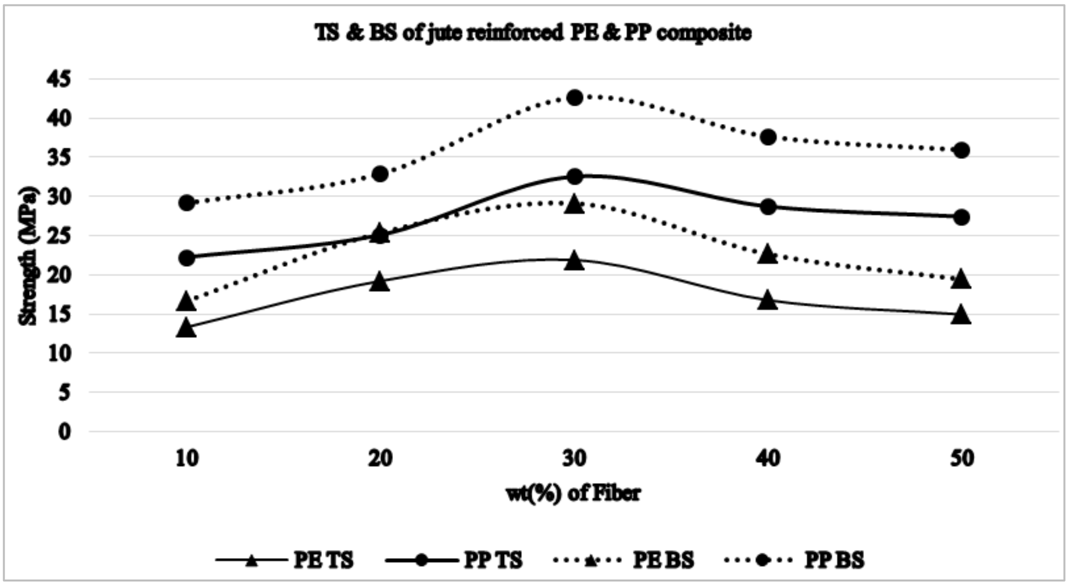


*Figure 6. Tensile Strength (TS) and Bending Strength (BS) of jute reinforced PE and PP composite against (wt%) of fiber content.*

### 5.1.2. Tensile Modulus (TM) and Bending Modulus (BM)

Tensile modulus (TM) is a measurement of a material's resistance to changes in length under tension or compression. It is also sometimes referred to as the modulus of elasticity. It is used to calculate the stiffness of an elastic material and is defined as the ratio of applied stress to strain. High TM materials are generally brittle, and low TM materials are generally ductile. Conversely, the bending modulus of a material is also known as the flexural modulus. It characterizes the material's rigidity, resistance to bending, or capacity for deformation under bending [27]. The TM and BM of the PE and PP composite in response to the weight percentage of jute fiber content are shown in Figure 7. The greatest TM and BM characteristics are seen in the figure for the 30% fiber content of jute reinforced PE composite. Whereas, the TM and BM of PP-based composites with fiber contents ranging from 10% to 30% increased by 0.53 GPa to 0.87 GPa and 0.44 GPa to 0.64 GPa, respectively. Conversely, the corresponding values for PE-based composites increased by 0.11 GPa to 0.74 GPa and by 0.25 GPa to 0.44 GPa, respectively. Following that, the TM and BM drop to 0.21 GPa and 0.29 GPa for composites based on 60 to 50% PE and 0.30 GPa and 0.54 GPa for composites based on 60 to 50% PP, respectively. This study unequivocally demonstrates that PP-based composites had much higher values of TM of 17.57% and BM of 45.46% than did PE composites reinforced with 30% of jute fiber content, and both composites exhibited the maximum mechanical characteristics when 30% of the material was made of jute fiber. This suggests that compared to PE-based jute reinforced composite samples, PP-based samples are more rigid and brittle.

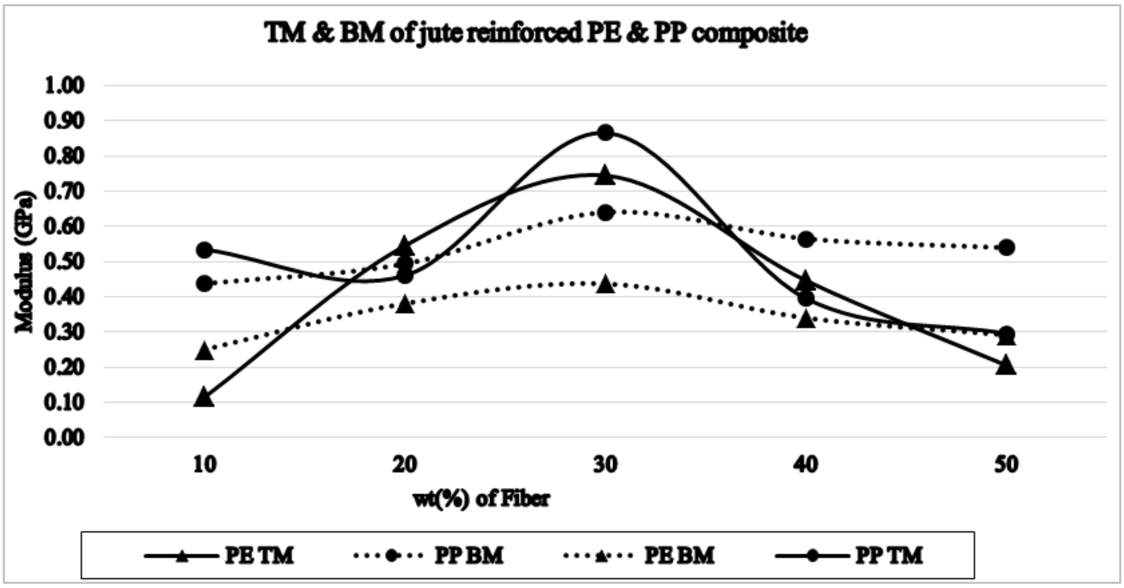


***Figure 7.*** *Tensile Modulus (TM) and Bending Modulus (BS) of jute reinforced PE and PP composite against (wt%) of Fiber content.*

### 5.1.3. Elongation at Break

The amount of buckling that a material can tolerate before breaking is known as its ductility. When a specimen's length increases by a total percentage during a tensile test, the result is the percent of elongation, which represents the material's permanent plastic deformation prior to failure [27]. Elongation break of jute reinforced PE & PP composite against (wt%) of fiber content is shown in Figure 8. For the PE based composites, the maximum elongation at break is 19.6%, whereas for the PP based composite, it is 12.2%, with a 50% jute fiber content. The high percentage of elongation indicates that the composite samples are less resistant to the imposed load. On the other hand, the minimal value of elongation at break for 10% of jute-reinforced composites is 12.4% and 7.4% for PE and PP based composites, respectively. Ultimately, the findings showed that, for jute reinforced composites based on polypropylene (PP), the value of elongation at break was lower than that of PE-based jute reinforced composites with fiber contents ranging from 10% to 50%. It is indicating that, in terms of elongation break, PP-based composites proved to be more appreciated than PE based jute fiber reinforced composite. However, it is evident that the elongation at break for the PP composite is lowest when the jute percentage is 30%, whereas the PE-based composite exhibits the least value when the jute content is 40%. It can be seen that both composite samples exhibit the maximum percentage of elongation despite having low tensile strength at 50% jute content. The reason for this is that some of the fibers are not breaking throughout the test because of the inadequate interfacial connection between the fiber and matrix. As a result, the sample displays a more elastic behavior [28].

### 5.1.4. Impact Strength (IS)

The capacity of a material to withstand sudden, strong impacts, or shock loads, without breaking, fracture, or plastic deformation is known as impact strength or toughness. The impact strength of the jute-reinforced PE and PP composite is shown in Figure 9 against the weight percentage of fiber content. The impact strength value for PP-based composites with a 30% fiber concentration is 13.37 kj/m2, but the value for the 30% fiber content jute reinforced PE composite exhibits the maximum value of 19.47 kj/m2. The PE-based jute reinforced composite samples absorbed more impact energy than the PE-based jute reinforced composite due to optimal fiber loading and appropriate adhesion between the fiber and the matrix. Conversely, the lowest impact strength values for composites with 90% of PP based composite and 50% of PE based composite are 9.17 kj/m2 and 13.66 kj/m2, respectively. According to the figure, which shows that the fiber content of PE and PP-based composites ranges from 10% to 50%, PE-based composites are more impact-resistant than PP-based composites.

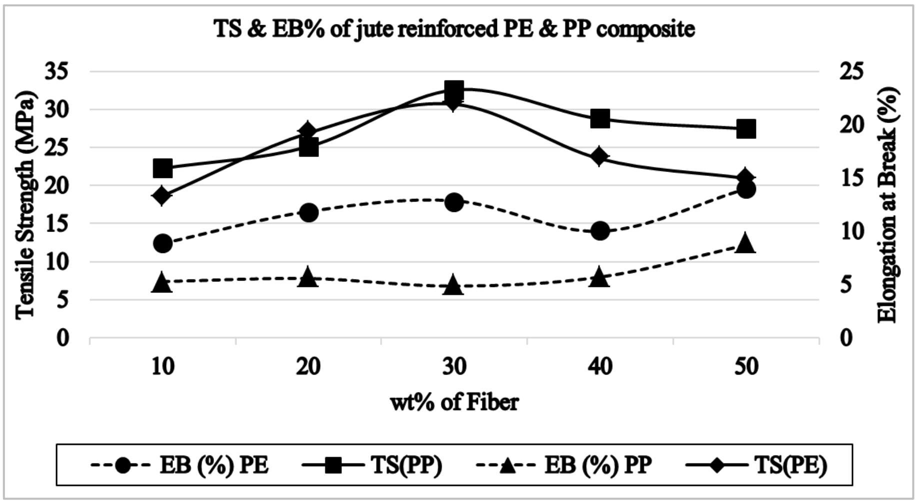


***Figure 8***. *Tensile Strength & Elongation Break of jute reinforced PE & PP composite against (wt%) of fiber content.*

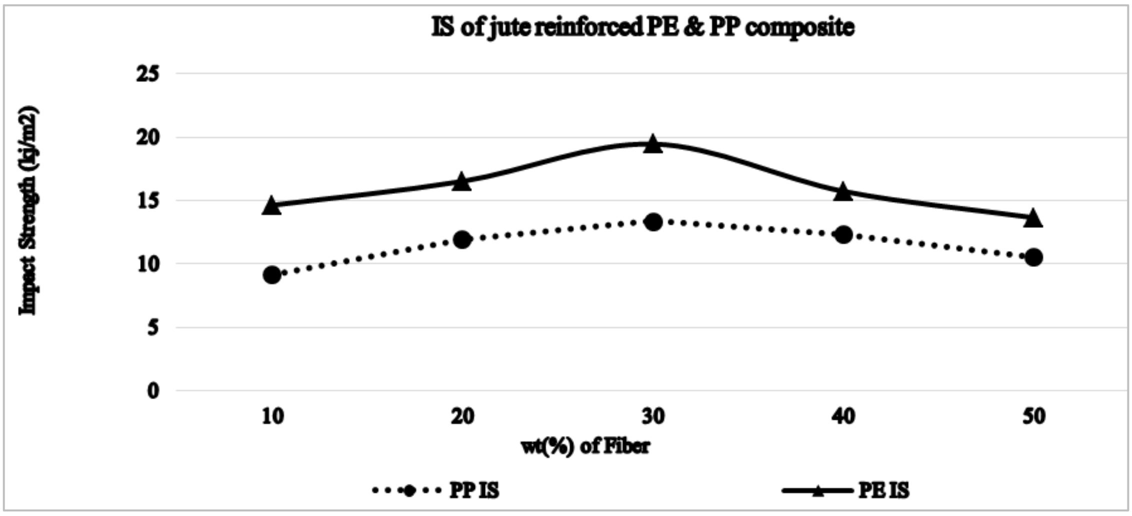


***Figure 9***. *Impact Strength (IS) of jute reinforced PE and PP composite against (wt%) of Fiber content.*

## 5.2. Water Uptake of the Composites

The adhesion between the fiber and the matrices determines the qualities of this unique composite. The matrix and fiber split as a result of insufficient adhesion, increased moisture absorption, and swelling. Thus, many methods have been attempted to date to alter both fiber surfaces in order to improve their adhesion and decrease their water absorption, including acetylation, silane, acrylonitrile grafting, maleic anhydride grafting, acrylation and isocyanate [29]. The samples of different weight percentage of jute reinforced PE and

PP composite's water-swelling behavior is determined by water uptake in order to improve comparison. In Figure 10 and Figure 11 the water uptake results (%) were plotted against the soaking time (hour) for jute reinforced PE and PP composite, respectively. It was demonstrated that the PP composite absorbs water at a significantly faster rate than the PE composite. In the early stages, both composites are soaking in more water than they will later on. However, at different soak times up to 50 hours, the PE composite's water uptake values increase to 0.13–0.35%, whereas the PP composite's values range from 0.23–0.44% for the same period of time. Up to a certain point, the amount of water absorbed rises with the length of soaking time; beyond that, no discernible water absorption occurs. On the other hand, it is clear that as the fiber content increase, samples of the composite material absorb more water.

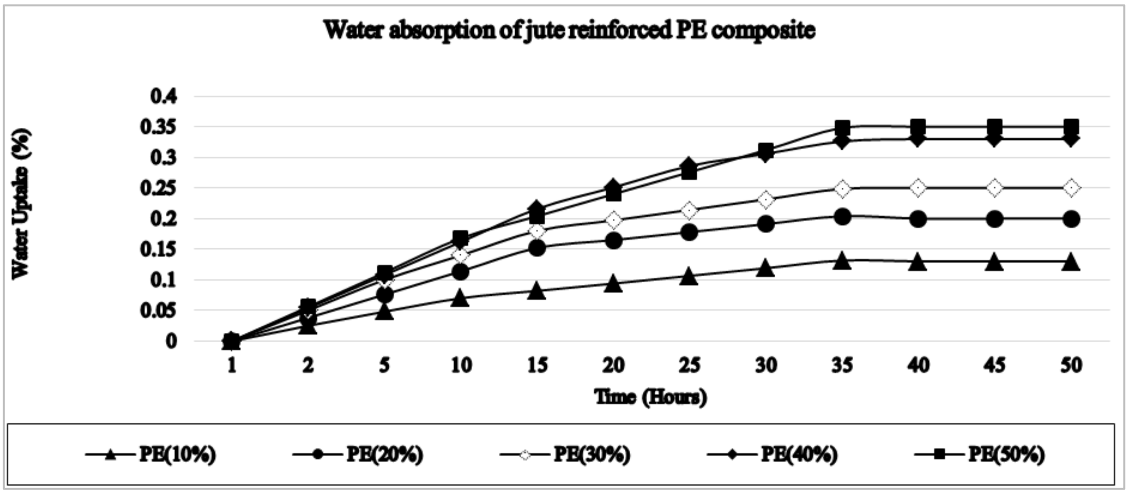


***Figure 10.*** *Water absorption of jute reinforced PE composite against (wt%) of fiber content.*

These phenomena can be explained by the hydro-d-glucose cellulose structure of jute, which is distinct in that it has three hydroxyl (-OH) groups. In moist air, the hydroxyl groups in jute cellulose interact with other cellulose molecules and hydrogen groups to generate intermolecular hydrogen bonds. However, the cell's collections of long-chain cellulose molecules contain both crystalline and amorphous areas. It is believed that in the crystalline region, the -OH groups of adjacent cellulose molecules are cross-linked or mutually bonded. Crystalline groups lack any locations where water can be retained or absorbed as a result [30].

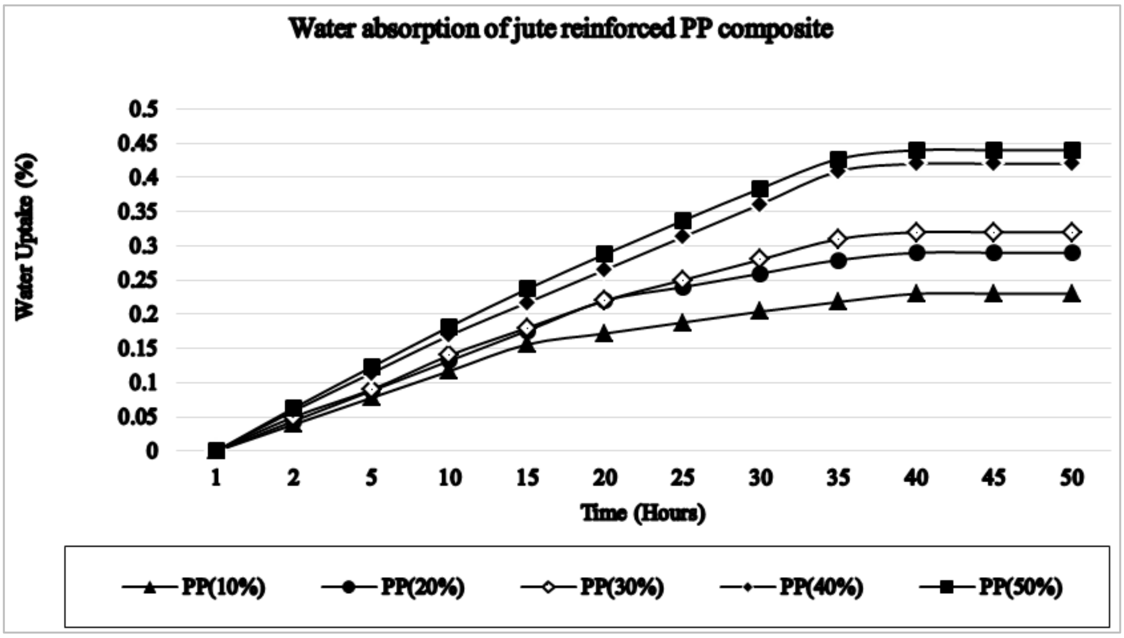


***Figure 11.*** *Water absorption of jute reinforced PP composite against (wt%) of fiber content.*

## 6. Conclusions

Compression molding was used to create jute hessian cloth, reinforced polyethylene (PE), polypropylene (PP) thermoplastic matrixes with a combination of (10 to 50%) of fiber loading by weight. It was discovered that the mechanical characteristics of the PP polymer matrix composites were comparatively higher than those of PE composites and 30% jute fiber and 70% (PE and PP) matrixes composites showed a greatest result of mechanical properties among (10 to 50%) of jute fiber composites. The water resistance qualities were also moderate of all those samples. In summary, we found an excellent performance and great mechanical characteristics at low weight of jute reinforced PE and PP polymer matrix composites, which can be a potential choice in future applications include the automobile industry, building interior construction, home or garden furniture and the toy sectors. To sum up, our study reveals the following important conclusions.

1. PP-composites exhibit significantly higher tensile strength, tensile modulus, bending strength and bending modulus compared to PE based composite, but PE-composites showing higher impact strength than PP.
2. Optimal tensile strength, tensile modulus, bending strength, bending modulus and impact strength for PE and PP based composite is with 30% of jute content.
3. Up to a certain point, the amount of water absorption rises with the length of soaking time and samples of the both composite materials absorb more water when the fiber content increases.

## Abbreviations

PP: Polypropylene
PE: Polyethylene
TS: Tensile Strength
TM: Tensile Modulus
BS: Bending Strength
BM: Bending Modulus
IS: Impact Strength
wt%: Weight percentage of fiber

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## Conflicts of Interest

The authors declare no conflicts of interest.

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