Optimizing the Fabric Architecture and Effect of γ-Radiation on the Mechanical Properties of Jute Fiber Reinforced Polyester Composites

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ABSTRACT: The fiber architecture can significantly influence the rate of impregnation of a resin in making composites and the load-bearing ability of individual fibers on testing of the loading directions. Moreover, achieving the maximum mechanical performance of a natural fiber composite selection of yarn liner density and optimization of fabric structure and further modification of the composites remains a great challenge for the composite research community. In this study, a number of jute-based woven derivatives (plain, 2/1 twill, 3/1 twill, zigzag based on a 2/2 twill, and diamond based on a 2/2 twill) have been constructed from similar linear densities of yarn. The effect of the fabric architecture and further modification of optimized composites by applying γ-radiation is also explained in this study. The experimental results show a 54% increase in tensile strength, a 75% increase in tensile modulus, a 69% increase in flexural strength, a 124% increase in flexural modulus, and 64% increase in impact strength of twill (3/1) structured jute fiber polyester composites in comparison to other plain and twill structured composites. A further mechanical improvement of around 20–30% is possible for the optimized twill structured composites by applying γ-radiation on the composites. An FTIR, TGA, and SEM study confirms the chemical, thermal, and fractographic changes after applying the modification of composites.

1. INTRODUCTION

Natural fibers are attracting significant interest in the field of fiber-reinforced polymeric composites due to the continuous increase of environmental awareness among environmental activists and consumers of the product all over the world. Moreover, the biodegradability of natural fibers make them attractive as reinforcements in composite materials. In addition, the availability, low cost, higher specific mechanical properties, low density, and better thermal and acoustic properties are considered the key selection parameters for developing natural fiber composites. Jute, flax, hemp, sisal, and kenaf are the main natural reinforcing materials currently used in the composite industry. Recently, using jute fiber in structural composite applications has created a great demand due to its tremendous benefits in terms of availability, cost, and performance over those of other natural fibers. However, a significant improvement in the strength of jute-fiber-reinforced composites is necessary to allow the use of jute fibers in the structural composite industry.

The mechanical properties of natural fiber composites are mainly governed by the fiber architecture, fiber placement technique, and the quality of the interface between the fiber and matrix. Natural-fiber-reinforced composites are made with different forms of architectures such as a unidirectional (UD) preform, plain woven, knitted, braided, and short-fiber preforms. Among all of them, knitted and braided preforms are not used very often in the composite research arena due to their high manufacturing cost and low composite mechanical performance. Short fibers also suffer from low tensile properties due to the orientation factor associated during the formation of preform. Though, recently, development and manufacturing of a UD continuous preform or tape has attracted a broader interest in the composite community due to the high load-bearing ability of parallel arranged fibers, improved fiber packing, and excellent interfacial shear strength. In most of the cases, this architecture still remains in laboratory-scale research and in some cases continuous short width UD tape. However, the high manufacturing cost, poor drape ability, and low damage tolerance mainly hinder this

Received: November 6, 2021
Accepted: March 4, 2022
Published: March 15, 2022
further, in a study on the effect of architecture it is also very essential to increase the compatibility of a natural fiber and the matrices. A natural fiber ideally shows less interfacial shear strength with matrices due to the presence of impurities such as hemicelluloses, lignins and waxes onto the surface of jute fibers. Chemical modification is a common technique that is largely used to improve the compatibility between the natural fiber and matrices. Using a chemical treatment is not sometimes feasible for the large-scale production of natural fiber composites. Rather, environmental concerns create an extra pressure on a composite researcher to adopt a sustainable modification of composites in order to render the performance of composites. Instead, modifying natural fibers by modifying the reinforced composites by \( \gamma \)-radiation has become a more preferred choice of the composite researcher community in the last few decades.

### 2. RESULTS AND DISCUSSION

#### 2.1. Mechanical Characterization of Composites

##### 2.1.1. Tensile Properties

Tensile testing is one of the effective ways of assessing the reinforcing ability of different textile architecture dry fiber preforms and the effect of modification of these preforms in composites. Ideally, the tensile strength and modulus of the composites depend on the tenable properties of the fiber and the quality of interfacial strength between the

### Table 1. Mechanical Properties of Jute Polyester Composites with Average Values

| sample | composite fabric type | resin type | tensile strength (MPa) | tensile modulus (GPa) | flexural strength (MPa) | flexural modulus (GPa) | impact strength (kJ/m²) |
|--------|-----------------------|------------|------------------------|----------------------|------------------------|------------------------|-------------------------|
| 1      | PC(1/1)               | polyester  | 31.5±(2.27)            | 1.18±(0.16)          | 57.02±(2.87)           | 1.7±(0.19)             | 10.06±(0.99)            |
| 2      | TC(2/1)               | polyester  | 37.56±(3.07)           | 1.69±(0.19)          | 77.54±(2.94)           | 3.12±(0.20)            | 13.21±(0.85)            |
| 3      | TC(3/1)               | polyester  | 48.74±(2.94)           | 2.07±(0.18)          | 96.56±(3.42)           | 3.81±(0.25)            | 16.43±(0.97)            |
| 4      | TZC(2/2)              | polyester  | 38.25±(2.71)           | 2.02±(0.12)          | 93.93±(3.56)           | 3.25±(0.25)            | 14.73±(0.88)            |
| 5      | TDC(2/2)              | polyester  | 35.84±(3.52)           | 1.52±(0.19)          | 64.18±(1.89)           | 2.29±(0.19)            | 12.72±(0.79)            |

fiber architecture in the use of bulk manufacturing of composites, whereas woven-based textile derivatives offer excellent scalability, as they can be manufactured by using a traditional power loom and have improved damage tolerance and better formability in making complicated designs in composites. Common woven textile architecture derivatives such as plain, twill, basket, and sateen are mainly used in textile composite applications. A large number of studies have been reported in the literature where natural fiber composites from woven derivatives were discussed. For example, Alavudeen et al. compared the plain- and twill-structured banana-/kenaf-fiber-reinforced composites polyester composites and found a plain architecture provides better mechanical properties than the twill structure. Similarly, Venkateshwaran et al. studied the effect of fiber architecture on the mechanical and thermomechanical properties of banana-fiber-reinforced polyester composites. Their study also reported that a plain architecture of banana fiber can provide improved mechanical and dynamic properties in comparison to the twill and basket architecture because of better interlocking of fibers in the warp and weft directions. A study by Pothan et al. has found better tensile and flexural properties for composites made with a mat architecture than the plain and twill weave architecture preforms due to the increased number of fiber arrangement in the loading directions. Similarly, Arju et al. compared the effect of woven and knitted jute fiber architectures in polypropylene-based thermoplastic composites and obtained better mechanical results for the twill fabric architecture. They claimed that a fabric with a twill structure has less crimp and a greater amount of fiber loading in the fiber direction when it is compared with other woven and knitted architecture preforms. Baghaei et al. compared different architecture hemp fiber preforms with a focus on a UD woven preform (higher amount of warp yarn). The study suggested that a satin weave offers better tensile, flexural, impact, and water absorption in comparison to a basket weave in composites due to the decrease in void content and misalignment of yarn. Thus, recent studies in the literature have obtained different results for different architectures which might be due to the use of different linear densities of yarn for different architectures. Therefore, it is very important to identify the exact architecture that is suitable for designing a particular composite with improved mechanical properties. A number of woven derivatives with the same linear density of yarn can provide a better insight into the composite performance.
fiber and the matrix. In this work, the effect of textile woven architectures with similar linear densities of yarn and the effect of dry modification of the composites have been evaluated by performing tensile testing and the results of the tensile properties are given in Table 1. In the case of the effect of fiber architecture tensile strength, the tensile modulus and elongation at break percent are compared in Figure 1a,c,e. It can be seen that the tensile strength and modulus of a plain architecture composite (PC) have significantly lower measured values in comparison to those of twill derivative composites. Generally, a plain architecture gives a loosely woven fabric; therefore, it is difficult to maintain the correct orientation of the fibers during the fabrication process.

As a result of that, relatively large percentages of crimp are formed after the fabrication process due to the interlacement of the warp (0°) and weft (90°) yarns (see Table 2).

During tensile loading of the composite fibers in the composite, the fibers need to be straightened out before they carry the load. This behavior of the plain architecture preform in the composites interrupts the stress development that reduces the significant value of tensile properties of the composites. However, on a comparison of twill weave architectures it is observed that TDC(2/2), TZC(2/2), and TC(2/1) composites show almost similar tensile properties but these are slightly higher than those of the PC composites. It is notable that the TC(3/1) composite has a significantly higher tensile strength (50 MPa) and modulus (2.2 GPa) in comparison to those of the other composites. Such a significant increase in tensile properties is related to the mode of design or architecture of the dry fiber preform used in the composites. The interlacement of the yarns in the TC(3/1) fabric having larger spaces in comparison to the other weave structures is mainly responsible for the lower crimp percent (see Table 3). As a result of that, the resin-rich area in the intersection area becomes smaller, thus reducing the stress concentration during tensile loading of the composites. On the other hand, to see determine the effect of physical modification on jute fiber composites, only the best of the weave architectures were selected and the modified composite tensile properties are shown in Figure 1b,d,f.

γ-Doses of different intensities were applied to the jute composite surface in order to optimize the intensity of doses for this particular weave structure. It can be seen that γ-radiation of 5 kGy gave the optimum tensile properties (see Table 2). The increase in the tensile properties of jute with increasing γ-radiation dose may be due to the inter-cross-linking between the neighboring cellulose molecules, which resulted in an increase in the strength of the natural fiber.

It is observed that the tensile properties increase with γ-pretreatment up to a certain limit (5 kGy) and then decrease due to two opposing phenomena, namely: photo cross-linking and photodegradation that take place simultaneously under γ-radiation. At lower doses, free radicals are stabilized by a combination reaction, and as a result, photo cross-linking occurs. The higher the number of active sites generated on the polymeric substrate, the greater the grafting efficiency. However, at higher radiation, the main chain may be broken down and the polymer may degrade into fragments; as a result, the tensile properties will decrease after certain γ-doses.

Table 2. Mechanical Properties of γ-Irradiated TC (3/1) Polyester Composites

| sample | radiation dose (kGy) | tensile strength (MPa) | tensile modulus (GPa) | flexural strength (MPa) | flexural modulus (GPa) | impact strength (kJ/m²) |
|--------|---------------------|-----------------------|----------------------|-----------------------|-----------------------|------------------------|
| 1      | UT                  | 49.94±2.67            | 2.13±0.22            | 95.8±2.66             | 3.27±0.20             | 16.56±1.02             |
| 2      | 2                   | 53.13±3.08            | 2.25±0.21            | 96.42±3.08            | 3.312±0.20            | 16.65±1.20             |
| 3      | 3                   | 55.43±2.94            | 2.33±0.22            | 103.13±2.95           | 3.55±0.19             | 16.86±0.99             |
| 4      | 4                   | 59.07±2.00            | 2.43±0.23            | 112.59±2.00           | 4.03±0.23             | 17.38±1.14             |
| 5      | 5                   | 65.8±3.52             | 2.54±0.24            | 121.31±3.52           | 4.23±0.23             | 18.59±1.00             |
| 6      | 6                   | 58.74±2.67            | 2.43±0.27            | 114.26±2.67           | 4.07±0.21             | 18.11±0.89             |
| 7      | 7                   | 55.31±2.05            | 2.23±0.14            | 115.54±2.05           | 4.01±0.19             | 17.81±1.25             |
| 8      | 8                   | 54.99±2.91            | 2.23±0.23            | 108.85±2.94           | 3.54±0.18             | 17.68±0.98             |
| 9      | 9                   | 50.34±2.85            | 2.21±0.24            | 102.99±2.84           | 3.62±0.24             | 17.19±1.25             |
It was observed that weave architectures have a great influence on the flexural properties of jute-fiber-reinforced composites. The highest amounts of flexural strength (100 MPa) and modulus (4 GPa) of the composites are attained for TC(3/1) composites. The trend of the tensile properties in the case of twill derivatives has been observed to be similar to that of the composites. The trend of the tensile properties in the case of different weave architectures to absorb energy. This absorbed energy is a measure of a given material's toughness and acts as a tool to study brittle ductile transition. In this study the Charpy impact properties of the composites made with different composites are compared in Figure 3a,b. It can be observed from the figure that the impact strength of composites has a

The effect of γ-radiation on the mechanical properties of jute-based composites is shown in Table 2 and Figure 2b,d. Here the flexural properties have improved with an increase in the dose intensity of γ-radiation. The maximum flexural strength (120 MPa) and modulus (4.5 GPa) was achieved for 5 kGy γ-radiation. When composites are exposed to γ-radiation, active free radicals are generated at polyester matrices, enhancing the interfacial connection between the fiber and matrix. In addition to this, these free radicals can be activated on the surface of jute fiber to change the internal structure of the fiber. Up to a certain dose of γ-radiation the intrachain bonds in the cellulosic part of the fiber can be altered to enhance the crystal orientation of the fibrils. As a result of the effect of the activation of the polymer, the fiber flexural properties of the composites have increased. However, a reduction in the flexural properties is responsible for the degradation or breaking of the polymer chain (primary bonds) with an excessive exposure of free radicals on the composite surface.

2.1.4. Impact Properties. Charpy impact tests without the presence of notches in the samples have been conducted to determine the ability of the composites made with different weave architectures to absorb energy. This absorbed energy is a measure of a given material’s toughness and acts as a tool to study brittle ductile transition. In this study the Charpy impact properties of the composites made with different composites are compared in Figure 3a,b. It can be observed from the figure that the impact strength of composites has a

Table 3. Physical Properties of Different Woven Fabrics Used in This Study

| fabric type   | crimp (short/weft way) (%) | crimp (short/weft way) (%) | area density (g/m²) |
|---------------|-----------------------------|-----------------------------|---------------------|
| plain         | 14.69 (±1.5)                | 12.69 (±1.2)                | 480 (±62)           |
| twill (2/1)   | 10.77 (±1.4)                | 11.46 (±1.2)                | 566 (±80)           |
| twill (3/1)   | 8.64 (±1.1)                 | 9.50 (±1.3)                 | 626 (±90)           |
| twill (zigzag)| 9.68 (±1.2)                 | 10.25 (±1.4)                | 557 (±55)           |
| twill (diamond)| 11.22 (±1.1)            | 12.61 (±1.2)                | 581 (±92)           |

It was observed that weave architectures have a great influence on the flexural properties of jute-fiber-reinforced composites. The highest amounts of flexural strength (100 MPa) and modulus (4 GPa) of the composites are attained for TC(3/1) composites. The trend of the tensile properties in the case of twill derivatives has been observed to be similar to that of the flexural properties. However, the PC composites has only a 60 MPa flexural strength and a 2 GPa flexural modulus. Such significant difference in the flexural properties between these two composites is connected to the alignment of the fiber printed in the machine direction of the composites and the interconnection between the warp yarn and weft yarn in the composites. It can be observed that TC(3/1) composites have higher amounts of yarn aligned on the axial directions, which helped to achieve a greater stress development and a lower stress concentration due to fewer amounts of fiber interconnection by warp and weft yarns in comparison to other weave architecture composites made with twill derivatives.

Figure 2. Bending property comparison of jute fiber composites: (a) effect of architecture on bending strength; (b) effect of γ-irradiation on bending strength; (c) effect of architecture on bending modulus; (d) effect of γ-irradiation on bending strength.

Figure 3. Impact and water uptake properties of jute polyester composites: (a) effect of architecture on impact strength; (b) effect of γ-irradiation on impact strength; (c) effect of architecture on water uptake percent; (d) effect of γ-irradiation on water uptake percent.
trend similar to those of the tensile and flexural properties on comparison with different weave architectures.

2.2. Water Uptake Percent. The impact strength of PC is only 10.06 kJ/m², whereas composites made from twill derivatives (TC(2/1), TC(3/1), TDC(2/2), and TZC(2/2)) have relatively higher impact strengths. The highest impact strength was noticed for T3C composites, 16.43 kJ/m². The higher impact energies of twill weave derivative composites are mainly because of the higher degree of fiber alignment in comparison to that in the plain architecture, as was discussed in an earlier section. The aligned fibers ensure a better matrix impregnation and less resin reaches areas inside the composites that delays the crack initiation and crack propagation. This behavior of the TC(3/1) composites thus confirms the fiber breakage instead of fiber pull-out, which may be true for PC composites due to poor interfacial adhesion between the fiber and the matrix. With an increase in γ-radiation the impact strength increases to 5 kGy, which causes a 12% increase in impact strength for TC(3/1) composites; further decreases in the impact strength occur for overirradiation, which is due to two opposing phenomena, namely, photo cross-linking and photodegradation, that take place simultaneously under γ-radiation.

For natural-fiber-reinforced polymeric composites it is necessary to assess the water uptake percent so that their viability in different applications can be justified. Cellulosic components of natural fibers have enormous amounts of hydroxyl groups that can easily absorb moisture in the fiber cell wall, which can cause a reduction in the interfacial shear strength between the fiber and matrix. As a result, swelling of fibers may occur inside the composites and thus change the dimensional stability and strength of the composites. In this study the water uptake percentages of the composites were measured as a function of the jute fabric weave architecture, and the results are shown in Figure 3c. It can be clearly seen that the weave architecture has little or no effect on the water uptake percentage of the composites used in this study. All of the composites made with different fabric architectures absorbed almost similar amounts of water. Such a behavior of the composites can be explained by the strongly hydrophilic nature of jute fibers due to the presence of polar groups (−OH groups) in its structure. The polar group forms hydrogen bonds by absorbing water molecules, and this induces swelling of the fibers.

Figure 3b shows the effect of variation of γ-radiation on the water absorbency of TC(3/1) composites and Figure 3c gives a comparison with untreated TC(3/1) composites. In this regard only 5 kGy γ-irradiated composites with PC and TC(3/1) composites were compared with their untreated composites due to the significant results in the tensile, flexural, and impact properties. It is interesting to observe that irradiated composites had dramatically reduced water uptake percentages of 50% in comparison with untreated composites for both woven architecture composites. The reduction in the water uptake percentage after irradiation of the composites is responsible for the reduction of (−OH) functional groups of the polyester matrices as well as of the jute fibers, which resulted in an improvement in the overall crystallinity of the composites by cross-linking between the functional groups of cellulose and polyester matrices.

2.3. Fractographical Analysis of Tensile-Tested Specimen. The observation of scanning electron microscope images is a popular way to assess the quality of fibers and degree of bonding between the fibers and matrices in composites. In this study, tensile fractured specimens of plain and twill architecture jute fiber composites have been examined to see the changes that occurred before and after the treatment of γ-irradiation. Figure 4a,b shows the SEM images of tensile fracture specimens of plain fabric architecture jute polyester composites before and after the application of γ-irradiation, respectively. It can be clearly seen from Figure 4a that for composites without γ-irradiation the pulled-out fiber morphology has a very smooth appearance in comparison to γ-irradiated composites (Figure 4b). A smooth appearance in the fiber morphology is related to the presence of impurities on the untreated jute fiber, which are commonly known as waxes, hemicelluloses, lignins, pectins, etc. Due to this fact, a cellular scale structure is visible on the fiber surface (see Figure 4a). Thus, the fractured specimen shows the nature of matrix failure with a higher degree of fiber pullout from the matrices (see Figure 4a).

However, composites made with a plain fabric architecture on treatment with γ-irradiation shows a completely mixed mode of failure. It is clearly visible from Figure 4b that the pulled-out fiber has a strong adherence of matrices on the fiber surfaces that promotes a strong interconnection of fiber inside the matrices. This indicates a strong interfibrilar adhesion between the fiber and the matrix. On the other hand, composites with a twill architecture without treatment show a scattered failure mode, where it is observed that a large number of fibers have been pulled out due to the poor interfacial shear strength between the fiber and matrix and at the same time fiber breakage shows a large irregular pattern (see Figure 4c). However, a composite with a twill architecture on treatment with γ-irradiation has a very strong interface and a very even mode of fiber failure during a tensile test (see Figure 4d). This behavior is similar to that of the composites made with a plain fabric architecture after treatment with γ-irradiation. Such a strong interfibrilar shear strength of the composites and even fiber breakage of composites after γ-
irradiation can be explained by the formation of large number of free radicals produced after the γ-irradiation, which helped to create a strong physical inter cross-sectional network between the jute fiber and polyester matrices.

2.4. Characterization of Untreated and γ-Irradiated Composites by FTIR. To identify the chemical changes in the composites before and after γ-irradiation in plain and twill architecture jute fiber composites, a FTIR study was conducted and the result of this study is illustrated in Figure 5. From the FTIR study, it can be seen that the peaks of the treated and untreated composites largely changed after application of γ-irradiation at a dose of 5 kGy. The main identical peaks can be observed at 2916 cm\(^{-1}\) which demonstrates the presence of enormous amounts of hydroxyl groups for these cellulosic composites. This peak intensity has largely changed and widened for irradiated composites (plain and twill with γ-irradiation) due to the large number of hydroxyl groups participating in forming hydrogen bonds in the composites. The peak intensity in the range of 2800–3000 cm\(^{-1}\) is ascribed to C–H stretching. The mode of the C–H stretching vibration is mainly related to the status of intermolecular interactions of C–H···O type present in the irradiated plain and twill polyester composites. Ideally, a large intensity of this peak confirms that weak hydrogen bonds exist in the jute fiber reinforced polyester composites treated with γ-irradiation. In this regard, the weakening of hydrogen bonds and release of molecular gases and free radicals after irradiation significantly affect the intensity of C–H stretching. The peak intensities at 1700 and 1260 cm\(^{-1}\) indicate the presence of carbonyl C–O groups in cellulose, hemicellulose, and lignins. Again, these peaks are greatly narrowed after the application of γ-irradiation for both plain- and twill-fabric-reinforced polyester composites due to the formation of cross-links with the help of free radicals. Thus, the FTIR study reveals that composites made from plain and twill architecture fabrics show a slight absorption of the identical peaks above whereas composites with γ-irradiation of the same fabric types show intense stretching of functional groups which contribute to the strong interfacial adhesion between the fiber and polyester matrices.

2.5. Analysis of Thermal Stability. The thermal stabilities of plain and twill composites both treated and untreated with γ-irradiation were estimated by a thermogravimetric analysis (TGA). In all four cases the primary degradation is observed at 95.0 °C, which may be due to moisture vaporization (see Figure 6). A significant degradation for all composites was observed between 316 and 417 °C. In the case of onset temperature and endset temperature neither untreated nor treated composites show significant differences, which confirms the slight effect of γ-radiation on the thermal stability of the composites. However, an improvement in both onset and endset temperatures is related to crystal changes of the treated composites after the application of a γ-radiation dose. This might be related to the cross-linking of the polymer with the help of free radicals on the composites further promoting a strong interfacial adhesion between the reinforcing materials and polyester matrices. The char residues of the treated composites reflecting an improvement in the thermal stability of the composites by creating a carbonaceous shield due to cross-linking of the polymer has also been in previous literature.

3. CONCLUSION

A number of woven jute fabric derivatives from similar linear densities of yarn have been constructed to compare their reinforcing performance in polyester-resin-based composites. The 3/1 twill structure exhibits better mechanical properties in comparison to the other twill structures and plain-fabric-reinforced composites. The tensile, flexural, and impact properties of the 3/1 twill structured composites were found to be greater in comparison to those of the plain and other twill derivative structure composites. The improvement in properties is related to the lower amount of crimp formation in the 3/1 twill structure. Therefore, this structure reduces the entrapped air between the yarn in the fabric which actually increases the impregnation of the resin and thus increases the load-bearing ability of fibers in the composites. Further ~24% and ~30% increases in the tensile and flexural properties being observed after application of γ-irradiation might be due to the increase in the degree of cross-linking between the fiber and polyester matrices, respectively. This study clearly demonstrates that selecting a suitable fabric architecture and using further γ-irradiation on composites can allow jute-fiber-based composites to be more commonly used in the structural composite market.
4. MATERIALS AND METHODS

4.1. Materials. Natural jute yarns made from high quality Tossa jute fiber origin from Hibiscus Canavinas were collected from the local jute spinning industry (Janata Jute Mill) in Bangladesh. In the manufacturing of jute yarn, jute fibers were treated with Batch Oil (emulsifier) to improve the spinning quality of jute yarn. The yarns used in this study were double-ply (two yarns twisted to make one yarn), and the linear density of the yarn was 5/2 lb/spindle. Unsaturated polyester resin was used as the main matrix material, and methyl ethyl ketone peroxide (MEKP) was added as a catalyst to accelerate chemical reactions; these were obtained from Nasim Plastic Industries, Dhaka, Bangladesh. The typical physical properties of polyester resin can be found in the work of Jannah et al.41

4.2. Methods. 4.2.1. Manufacturing of Textile Architecture Preform. Jute fabric preforms were manufactured using a conventional shuttle-based power loom from the same count of jute yarn.

A number of jute fabric architectures were produced from the same jute yarn in order to assess the quality of the fabric architecture in the reinforcement of composites. Briefly, a jute weaver beam was produced from a jute cone (jute yarn package) where porter (warp) yarns were arranged in parallel. In a power loom fabric manufacturing system yarns from the beams are passed through the heald eye and fixed in a cloth roller, where the manufactured fabric is collected (see Figure 7f).

On the basis of the requirement of the fabric structure a new drafting plan was applied to obtain a new architecture of fabric. Usually a short yarn (weft yarn) was placed in a widthwise direction by a picking mechanism. The schematic diagram of the weaving procedure is given in Figure 7f. The fabrics (plain, 2/1 twill, 3/1 twill, zigzag twill, and diamond twill) produced from a power loom are shown in Figure 7a−e). The physical properties of the fabrics were measured and are given in Table 3.

4.2.2. Composite Manufacturing. First, jute woven fabrics were cut into the desired size and dried in the oven at 100 °C for 1 h to remove the moisture from the fiber. The matrix material was prepared by mixing unsaturated polyester resin and 1% MEKP, mixed thoroughly before application to the jute fabric. A simple hand lay-up technique was adopted in order to impregnate the resin initially and then put it in a metal mold. Finally, the metal mold was placed in a hydraulic hot press machine (Carver, Inc., USA, Model 3925) at 105 °C for 10 min at 6 metric tons of pressure, and then the mold was kept at room temperature for 24 h to ensure better curing of composites. The coding system for different composites produced in this study is provided in Table 4.
Table 4. Symbols Used for Representing Different Form of Weaving Patterns in Jute Fiber Polyester Composites

| sample | weaving type | symbol     |
|--------|--------------|------------|
| 1      | plain (1/1)  | PC(1/1)    |
| 2      | twill (2/1)  | TC(2/1)    |
| 3      | twill (3/1)  | TC(3/1)    |
| 4      | zigzag twill (based on 2/2 twill) | TZC(2/2) |
| 5      | diamond twill (based on 2/2 twill) | TDC(2/2) |
| 6      | untreated twill (3/1) | UT       |
| 7      | plain (1/1) untreated | plain UT   |
| 8      | plain (1/1) γ-irradiated | plain TT   |
| 9      | twill (3/1) untreated | twill UT    |
| 10     | twill (3/1) γ-irradiated | twill TT   |

4.2.3. Irradiation of Reinforced Composites. After the optimization of woven structured composites, composites with 3/1 twill structure reinforced polyester composites were irradiated using a Co-60 γ-source (25 kci) at different doses (2–9 kGy) at the Atomic Energy Research Establishment, Savar, Dhaka, Bangladesh. This work was carried out on the basis of a study conducted on jute fabric oriented composites reported in the literature.8

4.3. Characterization of Composites. 4.3.1. Tensile Testing. The tensile strength of the composites was determined on a universal testing machine according to the ASTM D638-03 standard [99]. The specimen dimensions for the tensile test were 125 mm × 15 mm × 2 mm, a crosshead speed of 10 mm/min was employed during the tensile tests, and a gauge length of 50 mm was selected in the testing. Five specimens were tested for each sample type, and the average value with the standard deviation is reported in this study.

4.3.2. Flexural Testing. Static bending tests were carried out on a universal testing machine according to the ISO 14125 standard with a crosshead speed of 60 mm/s and a span distance of 40 mm as per the standard. The sample size was 60 mm in length, 15 mm in width, and 2 mm in thickness. Five specimens were tested for each sample types, and the average value with the standard deviation is reported in this study.

4.3.3. Impact Testing. Impact tests on unnotched composite samples were carried out according to the standard ASTM-D256. In this test method, the sample is mounted in a vertical direction. A pendulum weighing 2.634 kg fell freely on the sample, and the strike on the sample was lifted at an angle of 150°. There was an indicator that determined the specific angle when the pendulum struck the sample. Then the impact energy was calculated from the chart supplied with the impact tester.

4.4. FTIR and TGA Analysis. Fourier-transform infrared spectroscopy (FTIR) with a PerkinElmer System 2000 instrument was used to analyze the possible chemical bonds existing in the untreated and treated fibers. FTIR spectra were analyzed with an IR spectrometer in the range of 550–4000 cm⁻¹. The thermal properties of fibers with/witout treatment were investigated using a TA Instruments TGA apparatus (TA Q50, UK) within the temperature range of 25–600 °C at a heating rate of 10 °C min⁻¹ under a nitrogen atmosphere.

4.5. Microscopic Observation. The morphology of the fibers was observed by a Zeiss SUPRA 35VP field emission scanning electron microscope (FESEM). Samples were sputter-coated with 10 nm of gold in order to prevent damage to the fibers under the electron gun.

4.6. Water Absorption Study. The water uptake percentage (%) of the composites were determined according to ASTM D570-99 [103]. The test specimen was cut to a size of length ~39 mm and width ~10 mm. The cut samples were kept in an oven at 105 °C for 1 h. They were then taken out from the oven and immediately weighed. This weight was defined as W₀. Composite samples were immersed in a static water bath at 25 °C for different time intervals. After certain periods of time, samples were taken out from the bath, wiped using tissue paper, and then weighed. The water intake was determined by subtracting the initial weight from the final weight. This weight was defined as Wᵢ. Then the amount of water intake was calculated by the following formula:

water uptake (%) = \frac{Wᵢ - W₀}{W₀}

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A.Y.M.A.A. and F.S. jointly wrote the manuscript. A.Y.M.A.A. and S.A. conceived the idea and experimental design of the study. A.Y.M.A.A. performed all of the experimental work and analysis of the study. S.A. and F.S. reviewed, edited, and finalized the manuscript.

Funding
This research work did not receive any funding from external sources.

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Authors are grateful to Atomic Energy Research Establishment, Dhaka, Bangladesh, for allowing different characterizations of composites at their laboratory.

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