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Optimising Linear Density and Twist Factor for Enhanced Mechanical Properties of Jute Yarn/Bio-Epoxy Composites

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Abstract

This paper investigates the effect of the twist factor on composites made from jute yarns with different linear densities (193, 213, and 251 tex) twisted at four different levels (1460, 2420, 2820, and 3056 turns per meter x √tex). The results indicate that the composite made from the highest-density yarn required a lower twist factor to achieve the best mechanical properties. Specifically, the yarn with a linear density of 251 tex, twisted with a twist factor of 1460, exhibited the best mechanical properties with a tensile strength of 147.07 MPa, a modulus of elasticity of 13.7 GPa, and 1.36% elongation at break, at a volume fraction of 42%. In comparison, yarns with lower densities of 193 tex and 213 tex required a higher twist factor of 2420 to achieve their maximum properties. However, they demonstrated lower tensile strengths (122.49 MPa and 117.85 MPa), slightly lower moduli of elasticity (13.01 GPa and 11.67 GPa), and similar elongations at break (1.22% and 1.28%), at higher volume fractions (43% and 44%), respectively. The tensile properties of the composite show that higher strength was not achieved at the same optimum twist factor for the yarn's highest tenacity. Yarn made of 193 tex has the highest tenacity when twisted with 3056 (turns/m√tex), 213 tex at 2420 (turns/m√tex), and 251 tex at 2420(turns/m√tex), indicating that the impact of the twist factor can have different effects on yarn and its resulting composites. The analysis underscores the importance of balancing twist factor and yarn linear density for high-performance composites. It indicates that a low twist factor is necessary to keep the fibres parallel to the yarn axis and arrange them in the best direction for load-carrying capacity. The results indicate that the effect of the twist factor is linked to yarn linear density, addressing the ongoing challenge of balancing these two parameters for optimal composite performance.

Keywords: Jute fibre, Twist factor, Yarn linear density, Composite manufacturing, Composite evaluations.

Introduction

Composite materials have a rich history. Egyptians combined straw with clay as far back as 4000 BC, creating reinforced construction materials, indicating the early use of composites (Harris, 1984; Mansour et al., 2007). The 18th and 19th centuries saw a shift to iron, especially during the Industrial Revolution, due to its superior mechanical properties, such as high tensile strength and modulus of elasticity with less weight (Abed & Jawad, 2022). However, the 20th century brought about another shift with the introduction of polymers, ushering in a new era of composite materials. These new composites matched the mechanical strength of metals but with significantly lower densities, making them highly advantageous (Hsissou et al., 2021).

Polymers revolutionised the industry, allowing the creation of composite materials widely used in aerospace, automotive, construction, and sports sectors. Their lightweight nature, ability to withstand stress, and manufacturing flexibility have led to significant advancements in engineering design, paving the way for creativity and innovation (Sharma et al., 2018). Composite materials are composed of various materials, often referred to by their reinforcement materials or sources, such as fibre-reinforced polymer composites, metal matrix composites, and carbon matrix composites (Ekundayo & Adejuyigbe, 2019).

The first widely used fibre-reinforced polymer composites were made of synthetic materials derived from fossil fuel by products. These synthetic composites are non-biodegradable and non-recyclable, posing significant environmental challenges, including the production of greenhouse gases. As a result, natural fibre-reinforced polymer composites are now being utilised in non-structural areas of automobiles, aeroplanes, and buildings where load-bearing capabilities are unnecessary.

Researchers have enhanced the bonding of natural fibres with polar matrices through various chemical and physical treatments. Recently, spun yarn has been introduced to achieve a unidirectional arrangement of the fibres within the matrix, allowing for effective control of fibre orientation and enhancing the load-carrying capacity. This advancement supports reducing reliance on fossil fuels and their by products European (2017).

This study focuses on natural fibre-reinforced polymer composites, specifically those using jute fibres. Jute is the second most produced natural fibre, with an average length that can be spun into yarn (staple yarn) (Islam & Alauddin, 2012). Due to their specific properties, jute fibres are commonly used to produce non-structural composites to replace synthetic ones. Jute is a self-sustaining plant that grows easily in tropical regions of Africa and Asia with minimal care. When chemically processed, jute fibre's specific properties can be compared to that of e-glass fibre (Kandwal et al., 2019). Jute fibres, with a high aspect ratio, are spun into yarn to produce continuous strands aligned in the matrix, resulting in high-performance composites.

Many studies have investigated the mechanical properties of staple yarns, examining how twist level and yarn linear densities impact their performance as composite reinforcements. Dlodlo et al. (2009) and Jones and Rosenblum (2013) have indicated that these factors constrain the production of high-quality structural composites. Rask and Madsen (2011) studied unidirectional flax yarn composites to determine how twist angles affect their modulus of elasticity. They found that twist angles do not influence the modulus of elasticity, but uniform dispersion of the fibres within the composite will improve its stiffness.

Pinto, et al. (2014) studied epoxy composites reinforced with unidirectional jute yarn. The study revealed a tensile strength of 76.6 MPa and a modulus of 11.9 GPa. Madsen and Lilholt (2003) examined flax/polypropylene commingled warp yarns, finding axial stiffness ranging from 27 to 29 GPa and strength between 251 and 321 MPa for fibre weight fractions of 56 to 72%.

Ma et al. (2016) found that ramie yarn-reinforced composites experienced a substantial decrease in tensile strength beyond a specific linear density threshold, with lower linear densities yielding greater interlaminar strength. Banale and Chattopadhyay (2015) studied the effects of twisting and de-twisting yarn on fabric comfort, finding enhancements in softness, flexibility, and qualities such as wicking height and compressibility, though with trade-offs in air and water vapour permeability.

However, there is still a need to understand how the twist factor and yarn linear density interact and their effect on composites. This study fills this gap and makes a valuable contribution to the broader field of natural fibre composites.

Materials and Methods

Jute yarn

For this research, three single yarns of different linear densities with the same nominal twist factor were obtained from Bonanza Jute Composites & Diverse Factory Ltd. in Bangladesh. The three yarns' linear densities and twist levels were measured using Skein, a digital weighing machine with 0.001g accuracy, and a twist metre. The measurement results are presented in Table 1.

Table 1: Basic formation of the supplied yarn

Yarn identification (producer)(pounds/spindle of jute yarn)	Measured linear density (Tex)	Twist level *(turns per meter)*
5.6	193	174
6.2	213	166
7.3	251	153

The yarns underwent a retwisting process with four different twist factors of 1460, 2420, 2820, and 3056(*turns per metre x√tex*) using the Calvani Twisting Machine in the University of Manchester Textile laboratory. Table 2 shows the research sample plan indicating the number of yarn bobbins to be produced.

Table 2: Yarn specifications after retwisting

Jute Yarn Count		Twist factor (√ (tex) x turns per meter),			
		1460	2420	2820	3056
Tex	Ib/synpdle	TPM	TPM	TPM	TPM
193	5.6	105	174	203	220
213	6.2	100	166	198	200
251	7.3	90	153	177	190

After retwisting, the physical properties of the yarn were measured using a cross-sectional plate, as shown in Figure, to determine their cross-sectional areas and how the changes in the twist factor affect the physical properties of the yarns. Ten samples from each yarn were observed under a digital microscope and measured with a digital microscope measuring tool. The statistical results are shown in Table 3. The yarns are labelled by their density(tex) and factor(turns per metre x √(tex)).

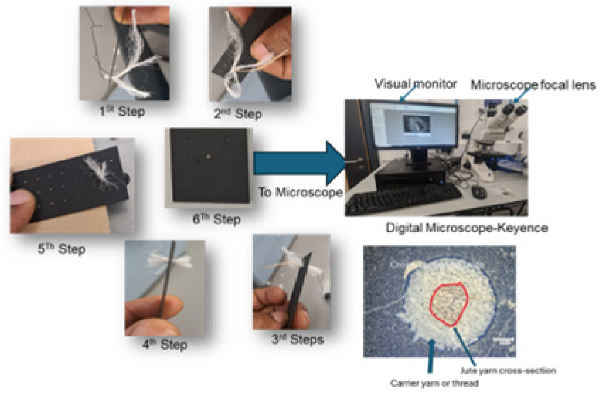

Figure 1: Illustration of preparing and measuring yarn or fibre cross-sections using a Digital Microscope.

Table 3: Statistical results of yarn cross-sectional areas affected by the twist factors.

Yarn Samples	Mean (um^2)	Standard Deviation	SE of mean	Coefficient of Variation
Y193T105	163225.00	51682.83	23113.26	0.32
Y193T174	199703.40	21831.86	9763.50	0.11
Y193T203	187782.60	9899.28	4427.09	0.05
Y193T220	229220.80	52519.47	23487.42	0.23
Y213T100	216058.00	35428.77	15844.23	0.16
Y213T166	242928.20	43864.83	19616.95	0.18
Y213T198	203032.00	18022.62	8059.96	0.09
Y213T200	348049.00	16707.61	7471.87	0.05
Y251T90	252538.20	37671.21	16847.08	0.15
Y251T153	221598.60	35256.59	15767.23	0.16
Y251T177	298718.80	41262.79	18453.28	0.14
Y251T190	234884.00	50935.74	22779.15	0.22

Tensile testing was conducted on the yarns according to ASTM D2256, with gauging of 250mm, a crosshead speed of 300mm/min, and a load cell of 100N (Belaadi et al., 2016). The results of the tensile properties of the yarns are summarised in Table 4.

Table 4: Tensile properties of single jute yarns

Yarn ID	Yarn Tensile Modulus cN/tex	Tenacity (cN/Tex)	Elongation at break (%)
Y193T105	536.76±146.70	12.4±4.5	2.27±0.50
Y193T174	813.98±836.60	14.6±2.7	1.79±0.20
Y193T203	686.34±148.90	17.8±3.5	2.60±0.20
Y193T220	818.02±111.10	23±3.5	2.80±0.50
Y213T100	341.19±168.60	8.0±3.70	2.60±0.70
Y213T166	948.15±980.80	22±3.70	2.32±0.30
Y213T198	889.23±666.20	21.4±3.00	2.40±0.30
Y213T200	912.91±114.90	21.3±3.30	2.40±0.50
Y251T90	615.57±104.50	14.74±3.50	2.40±0.80
Y251T153	984.31±742.10	28.4±2.10	2.90±0.10
Y251T177	938.86±139.80	27.8±5.50	2.90±0.30
Y251T190	852.98±929.50	22.6±2.90	2.70±0.90

Composite Manufacturing

The jute/bio-epoxy composites used in this study were made using jute yarn and LB 2 Laminating bio-epoxy resin supplied by Easy Composites Ltd., UK. The resin contains 35% biomaterials to enhance its biodegradability. Table 5 presents the key properties of the resin. Figure 2 shows the procedure for producing the composite laminae. A self-designed automatic winding machine was constructed to wind the yarns on a Polylactic acid (PLA) plate of 300mm x 300mm; the yarns unidirectionally at 0^{O} orientation. The preformed composites were dried at 60^{o}C for 4 hours to remove moisture. After that, the vacuum bag mould was prepared, and the vacuum infusion process was used to fabricate the composite laminae. The resin/hardener mixing ratio was 100:27, and it was degassed to remove air bubbles before it was infused in the mould. After infusion, the composites and the bag were left to cure for 24 hours. After that, the mould cover is removed, and the lamina composites are left in the open for 24 hours before finally being cured in the oven at 120^{O}C for 2 hours. The weight of the wound yarn was measured to calculate the volume fraction of each lamina composite. This was done by subtracting the weight of the PLA plate from the weight of the wounded plate. After the composite lamina was manufactured, the weight of the final composite was also measured. The volume fraction was then calculated using Equation 1.

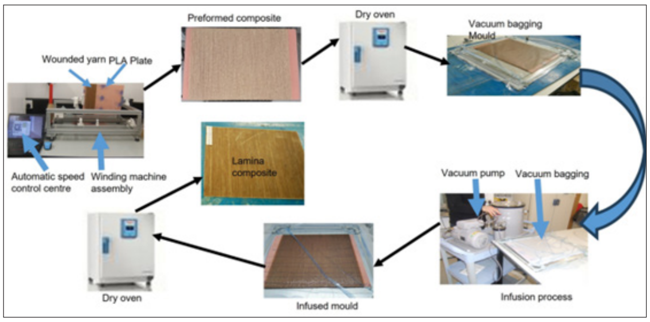

Figure 2: Complete procedure for the production of the jute/bio-epoxy composite laminae

$$Yarn\ volume\ fraction(V_y) = \frac{\frac{W_{yf}}{\rho_y}}{\frac{W_{yf}}{\rho_y}+\frac{W_{rf}}{\rho_r}} \qquad (1)$$

Where, Yarn weight fraction =W_{yf}; yarn density = ρ_y;
resin weight fraction W_{rf} Resin density=ρ_m; and
yarn volume fraction =V_y

The weight fraction of the yarns and resin were determined from equations 2 and 3.

$$Yarn\ weight\ fraction\ (W_{yf}) = \frac{W_y}{W_c} \qquad (2)$$

$$Resin\ weight\ fraction\ (W_{rf}) = \frac{W_r}{W_c} \qquad (3)$$

w_c = weight of the lamina composites

The results of the individual weight of the yarns according to their linear densities and the weight of the resin as calculated from equations 2 and 3, combined with the densities of the yarns according to their linear densities and the cross-sectional areas of the yarns after twisting, show the laminae composite compositions in Table 5.

Table 5: Composites composition

Composite ID	w_{yf}(%)	ρ_y (Kg/m^3)	W_{mf} (%)	ρ_m ($\frac{Kg}{m^3}$)	V_y(%)
YC193T105	36	1180	64	1130	35
YC193T174	39	970	61	1130	43
YC193T203	36	1030	64	1130	38
YC193T220	29	840	71	1130	35
YC213T100	34	990	66	1130	37
YC213T168	38	880	62	1130	44
YC213T198	38	1050	62	1130	40
YC213T200	30	610	70	1130	44
YC251T90	39	990	61	1130	42
YC251T154	43	1130	57	1130	43
YC251T177	38	840	62	1130	45
YC251T190	31	1070	69	1130	32

Yarn weight fraction =W_{yf};

yarn density =ρ_y; resin weight fraction W_{rf} Resin density=ρ_m; and yarn volume fraction =Vy and C= Jute yarn composite

Evaluation of Mechanical Properties

Tensile test

Tensile tests were done on five 25 x 250 mm samples of each composite lamina using the Instron Universal Testing Machine 5967 B with a 5KN load cell, as shown in Figure 4. The tests were done according to ASTM D3039 (Aggarwal and Chatterjee (2023); (Ma et al., 2016; Wang et al., 2019). The crosshead speed was set to 2 mm/min, and the gauge length was 150 mm. Dimensional checks of the specimen were carried out to ensure compliance with standards as the composites varied in thickness. Specimens were secured using 50-mm Emery paper to prevent slippage.

An extensometer with a 50 mm gauge length was attached to monitor the strain in real time for accuracy.

Origin software was used to calculate Young's modulus, tensile strength, and elongation at break.

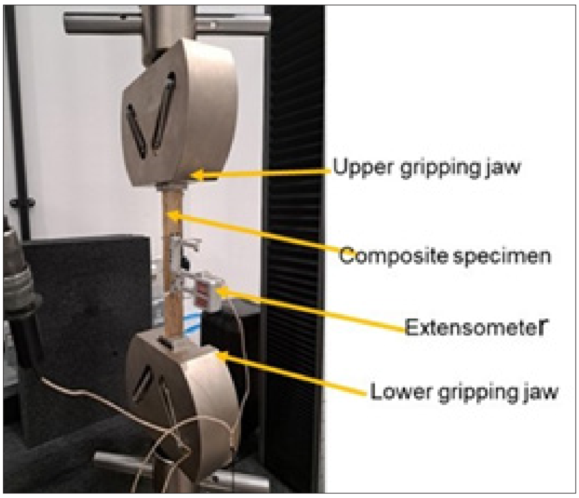

Figure 4: Tensile test

Flexural Test

Rectangular specimens measuring 60 mm x 13 mm x 0.8 mm were prepared in accordance with ASTM standards specified in document number D7264, and the experiment was conducted with the span-to-thickness ratio of 60:1 (Raheem, 2020; Taele et al., 2022).

The universal testing machine (UTM) had a 2kN load cell, and the tests were carried out at a crosshead speed of 2 mm/min. The load is applied at the centre to exert the flexural load until the specimen fractures. The 3-point flexure, which is the most common flexural test, as shown in Figure 5, was utilised. The load is applied at the centre to exert the flexural test until the specimen fractures. Five samples from each composite were tested and categorised by twist factor and linear densities.

Data from the machine's integrated computer was used to develop the flexural stress-strain curves and Origin software was used to determine the composite's flexural strength, modulus of elasticity, and elongation at break (Gopinath et al., 2014; Zaidi et al., 2018).

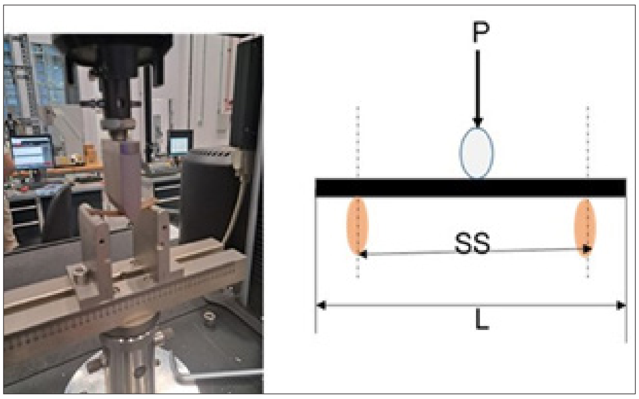

Figure 5: Flexural test

Impact Test

The impact test specimens were prepared according to the ASTM D 7136 standard, with 85mm x 55mm dimensions. Testing was carried out using the Instron Dynatup machine (CEAST9350), equipped with Blue Hill software and a drop-weight impetus, as depicted in Figure 6. The 2.045 kg machine impactor was positioned at a 60mm distance to impact the 40mm diameter area of the samples. The attached computer recorded the activities during testing, and the material's thickness was set at 0.8mm±0.25. After the test, the data extracted from the computer was used to create a graph of force-energy-displacement to determine the total energy absorbed by the samples before failure. The impact strength was determined using the formula:

$$Impact\ strength = \frac{Energy\ absorbed}{Impacted\ cross-sectional\ areas\ of\ the\ sample} \qquad (4)$$

Results and Discussions

Effect of twist factors on the cross-sectional areas of yarns according to their linear densities

Table 3 presents an analysis of the statistical means of the yarns' cross-sectional areas based on their linear densities and twist factors. The yarns' nominal twist factor was 2420 (turns·m-1·tex-1/2) before the retwisting. The table shows that the retwisting of the yarn leads to a decrease and increase in the cross-sectional areas. Reducing the twist factor requires that the yarn is twisted in the opposite direction("S"), during which the yarn fibre is pulled apart, decreasing the yarn density and increasing its cross-sectional area. However, the resultant effect of the twist factor depends on the yarn linear density (Y193T105, Y213T100, and Y251texT90). Meanwhile, an increase in the twist factor causes the fibres within the yarn to compress and close the gaps, increasing the yarn density and decreasing its cross-sectional areas (Y193T203, Y213T166, and Y251T153). Further, the increase of the twist factor with yarn fibres experiencing compressibility limits and the yarn density remain unchanged due to excessive titling of fibres, the yarn cross-sectional increases slightly (Y193T220, Y213T200, and Y251T190. The degree of fibre compression is influenced by the yarn's linear density and the twist factor. These results are in agreement with Pan (2022).

Figure 7 shows a graphical representation of the effect of the twist factors on the cross-sectional areas of yarns according to their linear densities.

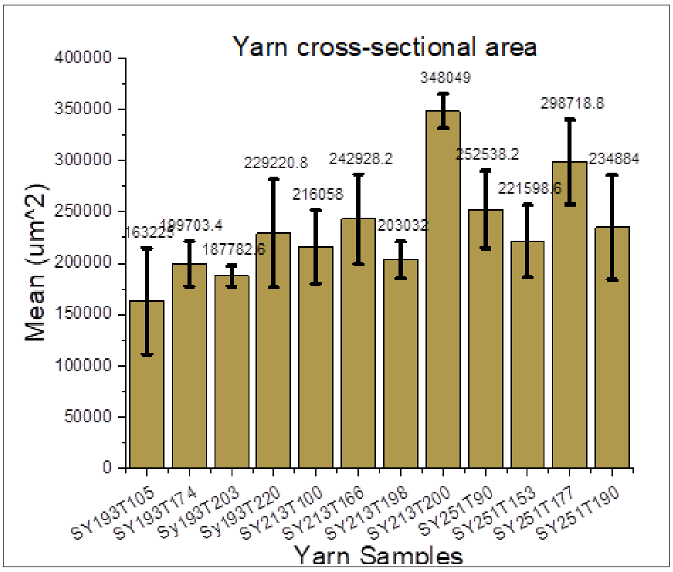

Figure 7: Effect of twist factor on jute yarn cross-sectional areas

In summary, the twist factor impacts the cross-sectional area of the yarn differently depending on the yarn's linear densities. These results show how varying the twist factor of yarns can affect their physical properties, which may, in turn, affect their mechanical properties, such as their strength, stiffness, and the yarn elongation at break. These research results are in tandem with the reported literature (Md Sohanur, 2015; Pan, 2022; Testex, 2022).

Table 4 displays the average tensile properties of jute yarns categorised by their linear densities. The chart in Figures a, b, and c depicts the impact of twist factors on these jute yarns.

The results indicate that twist factors affect the strength of jute yarns differently based on their specific twist factors. In Figure a, the tenacity of the 193tex yarn continues to increase as the twist factor increases. Figure b shows that the tenacity of the 213tex yarn also increases with the twist factor but declines sharply when twisted with a twist factor of 2820 turns per meter x √tex. Similarly, Figure c demonstrates that the tenacity of the 251tex yarn increases with the twist factor but declines at the same twist factor of 2820 turns per meter x √tex. The maximum tensile strength of the 193tex yarn is achieved at 23 cN/tex when twisted with a twist factor of 3056 turns per meter x √tex. Both the 213tex and 251tex yarns reach their maximum tensile strengths at 22 cN/tex and 28.4 cN/tex, respectively, when twisted with a twist factor of 2420 turns per meter x √tex.

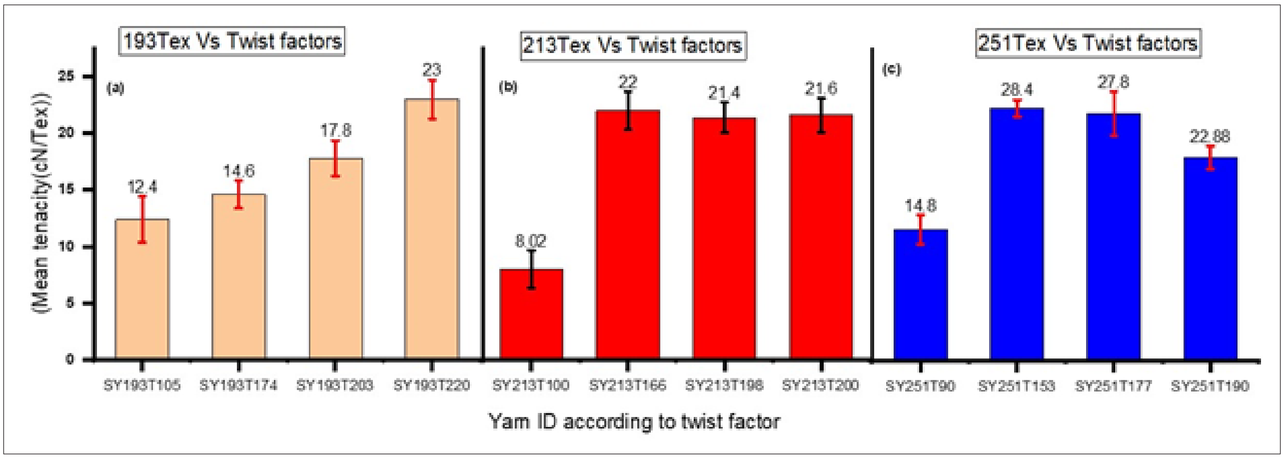

Figure 8: Tensile strength of single yarns

The twist factors influenced the tensile strength results of the different yarn linear densities, which were analysed using a one-way ANOVA to determine significant differences between and within each group of tested yarns. The analysis was conducted with a statistical significance level set at F > p value 0.05. The results of this statistical analysis are presented in Table 6.

Table 6: One-way analysis of variance (ANOVA) of the influence of twist factors on the Tensile properties of yarns according to their linear densities

Source of variation	DF	Sum of Squares	Mean Square	F Value	Prob>F
SY193Tex-Tenacity	3	317.75	105.91667	7.80233	0.00197*
SY213Tex-Tenacity	3	699.3015	233.1005	19.47291	0.0000137*
SY251Tex-Tenacity	3	592.854	197.618	14.25121	0.0000879*

The results can be explained in two ways. First, the twist factors required for the yarn to reach its maximum tensile strength depend on its linear density. Second, once the critical twist factor for the yarn, based on its linear density, is reached, the yarn reaches its maximum strength. Additional twist factors beyond this point will cause more misalignment of the fibres and increase the off-axis angle to the yarn axis, which will decrease the yarn's strength. The obtained tensile properties of the jute yarn are comparable with other reported results (Aggarwal & Chatterjee, 2023).

Tensile properties of jute bio-epoxy composites

In Figure 9(a-c), the average results of the jute bio-epoxy composites (JYC) are presented and analysed. The figures show the tensile strength and modulus of elasticity, elongation at the beak and the volume fraction of the JYC. The tensile strength of composites largely depends on the mechanical properties of the reinforcement materials, the volume fraction of fibres in the composites, and the interfacial strength of the fibre or yarn with the resin. The interface quality between the jute yarn and bio-epoxy resin and the level of yarn twist play a crucial role. Specifically, the twist factor affects the composite's overall performance; as the twist factor increases, it reduces the gaps between fibres, thereby hindering resin flow into the core fibres in the yarn. (Lau et al., 2018; Ma et al., 2016).

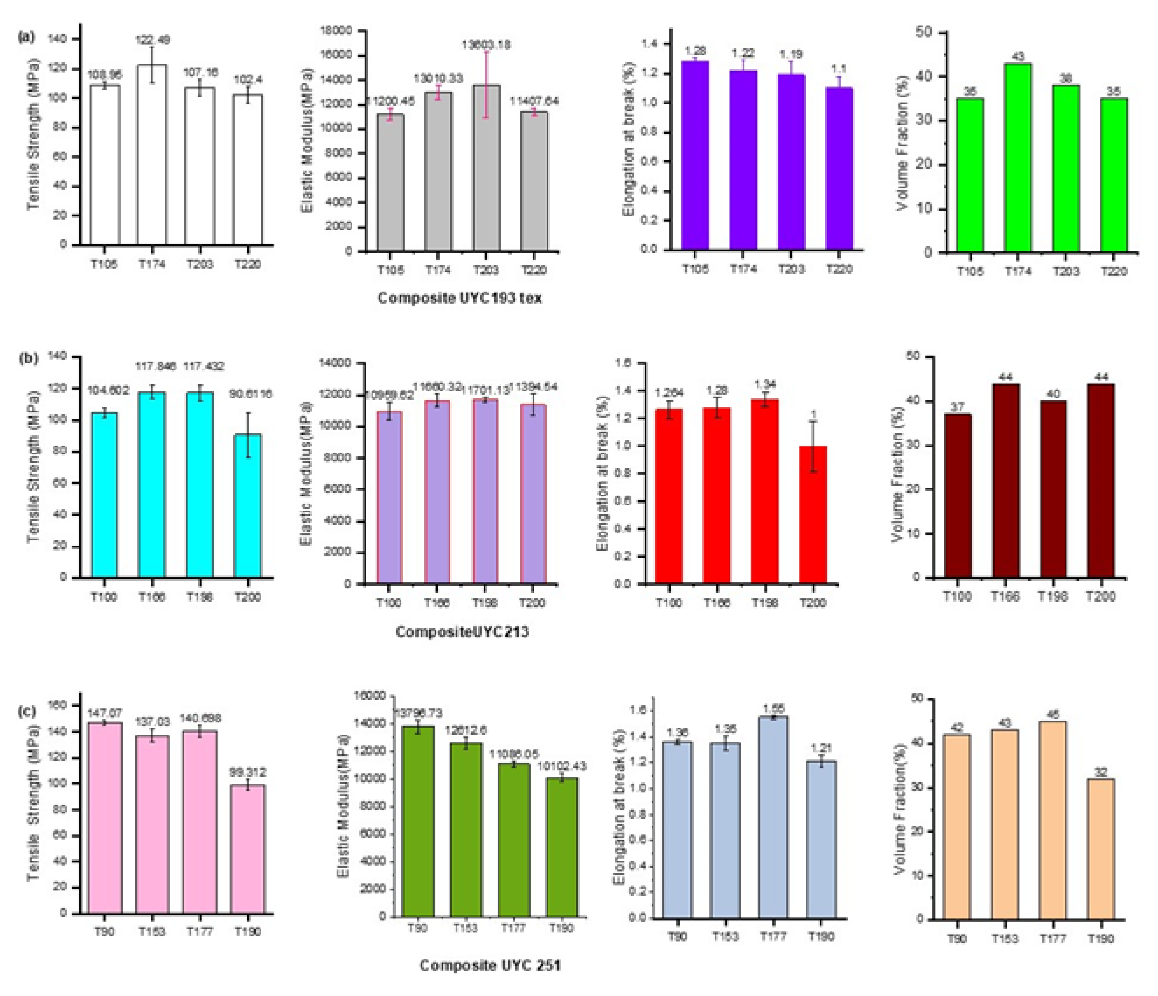

Figure 9(a-c) : Tensile properties of jute yarn bio-epoxy composites made of 193tex, 213tex and 251tex.

As the yarn's linear density increases, the twist factor(turns·m-1·tex-1/2) decreases, which is expected to cause differences in the interaction between the yarn/resin interface(Ma et al., 2016).

As the yarn twist factor increases, the composite strength increases until the optimum balance between the yarn's linear density and the twist factor is reached. Hence, a further increase in the twist factor leads to a decrease in the strength of the composites (Madsen, 2004).

After analysing the results, it was found that composites made of 193tex(Figure 9a) showed maximum tensile properties when the yarn was twisted with a factor of 2420 turns·m-1·tex-1/2. The composite strength declined with a further increase in the twist factor. Additionally, the volume fraction of the composites plays a critical role in determining their tensile properties, as an increase in the yarn volume fraction also increases the strength of the composites.

Figure 9b illustrates the tensile properties of jute yarn bio-epoxy composites of 213tex yarn. The impact of the twist factor on the composites made from the 213tex yarn was similar to those made from the 193tex yarn. The tensile properties of the composites improved as the yarn's twist factor increased, and the best composites were produced when the yarn's linear density and twist factor reached their optimal balance at C213T166. This was achieved when the yarn was twisted with 2420 (turns·m-1·tex-1/2). The composite exhibited a tensile strength of 117.85MPa, a modulus of elasticity of 11.67GPa, and a breaking strain of 1.28%, with a composite volume fraction of 44%. The differences in the properties of C213T166 and C213T200 highlight the influence of the yarn's twist factor, even with the same volume fraction of 44%. An increase in the twist factor led to an increase in the yarn twist angle and the tightness of the fibres within the yarn, which in turn increased the resistance of the yarn to resin penetration, coupled with fibre misalignment and obliquity.

Figure 9c illustrates how the twist factor impacts the tensile properties of composites created with 251tex yarn. As the twist factors were used to twist different jute yarn and increase the yarn's linear density, the level of twist was reduced. The 251tex yarn was twisted with twist levels ranging from 90t.p.m to 190t.p.m. The results show that the composites with the lowest twist level, C251T90, wherein the yarn was twisted with 1460 turns per meter, had a tensile strength of 147.07MPa, a tensile modulus of 13.80GPa, and an elongation at break of 1.36%, with a yarn volume fraction of 42%. Moreover, increasing the twist factors further reduced the composite properties, even with increased volume fraction. The obtained tensile properties of the composites made from each yarn linear density according to their twist factor are comparable with other reported results (Ma et al., 2016; Madsen et al., 2007; Zaidi et al., 2018; Zhang & Miao, 2010). Figure 11 shows that the composites made from C251T90 yarn showed the highest tensile strength of 147.07MPa among the three yarn linear densities used for composite manufacturing.

An analysis of variance (ANOVA) was conducted to evaluate the impact of the twist factor on the tensile properties of jute bio-epoxy composites. The properties analysed include tensile strength, modulus of elasticity, and elongation at break across various composites of yarn linear densities (C193, C213, and C251). The significance level was set at $p<0.05p$.

Table 7: Analysis of ANOVA Results on the Influence of Twist Factor on the Tensile Properties of Jute Bio-Epoxy Composites

Sources of variation	DF	Sum of Squares	Mean Square	F Value	Prob>F
JYC193-Tensile strength	3	1113.42449	371.1415	1.32653	0.30057
JYC213-Tensile strength	3	2496.2019	832.0673	2.63834	0.08505
JYC251-Tensile strength	3	6963.91662	2321.30554	27.59712	1.46E-06*
JYC193-Moludus of elasticity	3	2.10E+07	7013434.966	0.7197	0.55468
JYC213_Modulus of elasticity	3	1745333.916	581777.972	0.45064	0.72034
JYC251-Modulus of elasticity	3	4.00E+07	1.33E+07	19.23468	1.48E-05*
JYC193-Elongation at break	3	0.07909	0.02636	1.01336	0.41262
JYC213-Elongation at break	3	0.33982	0.11327	1.96815	0.15945
JYC251_elongation at break	3	0.29222	0.09741	13.63738	1.13E-04*

*significant difference

The ANOVA table reveals that the twist factors do not significantly impact the tensile properties of the composites made from 193tex. The p-values for the composite's tensile distribution are 0.30057 for tensile strength, 0.55468 for modulus of elasticity, and 0.41262 for elongation at break. Similarly, the twist factors have minimal impact on the tensile properties of composites made of 213tex. This is supported by the p-values, all of which are greater than 0.05 (p-0.08505 for tensile strength, p-0.72034, and p-0.15945). Nevertheless, the p-values reveal a noteworthy impact of the twist factor on the tensile properties of composites made from 251tex. The p-values for tensile strength modulus of elasticity and are 0.00000146, 0.0000148, and 0.000113, respectively.

Based on the ANOVA results, the twist factor significantly impacts the tensile strength, modulus of elasticity, and elongation at the break of the jute yarn composite C251. However, the twist factor does not significantly impact the tested tensile properties for C193 and C213.

The observed effects in C251 indicate that the twist factor is very important in determining the mechanical properties of jute bio-epoxy composites with higher linear densities. Thus, it is crucial to optimise the twist factor when working with composites with higher yarn linear densities by using the appropriate low twist factor strong enough to hold the fibres and keep them in their positions of orientation during production to attain the desired mechanical properties for structural applications.

Effect of Twist Factor on the Flexural Properties of Jute Bio-Epoxy Composites

Figure 10 (a-c) shows the results of the flexural tests conducted on composites with different yarn linear densities (tex). The flexural properties were measured using the flexural-strain graphs derived from the tests. Figure 10:

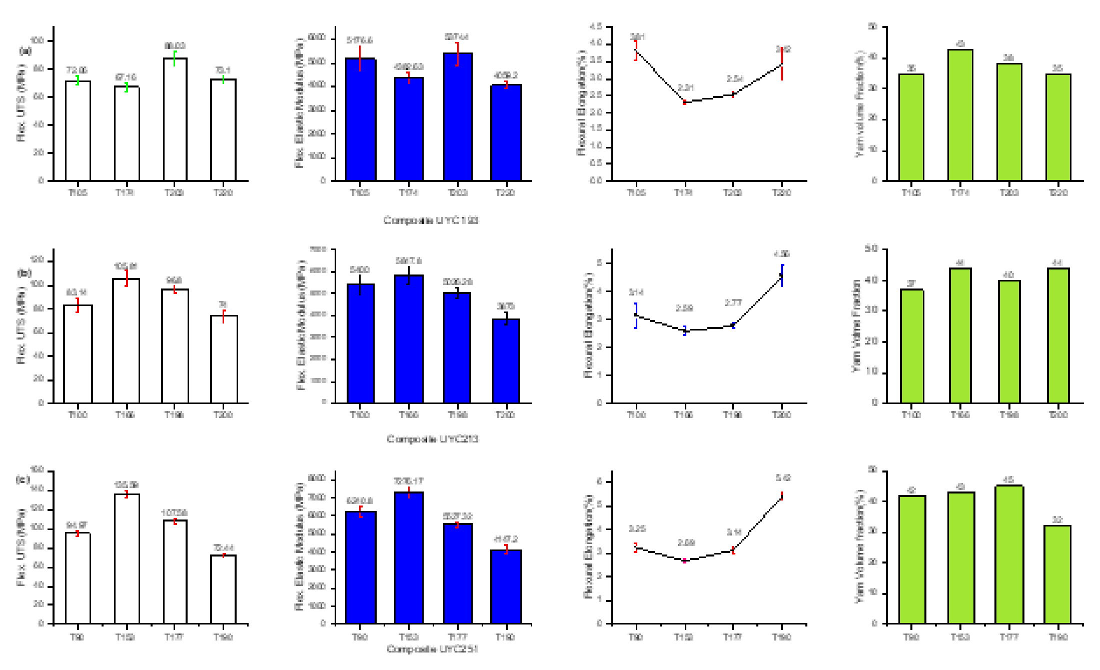

Figure10(a-c): Flexural properties of composites of 193tex,213tex and 251tex

The findings show that the flexural strength of the composites, made of 193tex yarn (Figure 10a), increases with the yarn twist factor up to a certain point before it starts declining. Specifically, the maximum flexural strength, flexural modulus and failure strain were achieved at 88.03 MPa, 5.37GPa and 2.54%, respectively, at a volume fraction of 38%, when the composite yarn was twisted with 2820 (turns·m-1·tex-1/2). Although the composite exhibited high flexural strength and modulus, its elongation at break was not the lowest. This implies that while the material was strong and stiff, it still had some ability to deform before breaking. The report suggests that the slight increase in the failure strain (elongation at break) could be due to fibre breakage during retwisting. This process likely introduces irregularities in the fiber length within the yarn.

Figure 10b illustrates the flexural properties of composites made of 213tex; similar to the composites produced from 193tex, the results of the flexural test carried out on composites made of 213tex showed an increase in flexural strength as their yarn twist factor increased; the highest flexural strength was recorded when the composite yarn was twisted with a twist factor of 2820(turns·m-1·tex-1/2), with the flexural strength, flexural modulus, and failure strain being 105.81 MPa, 5,85GPa, and 2.59%, respectively, at a volume fraction of 44%.

Figure 10c illustrates the flexural properties of composites made of 251tex. The results of the flexural strength of composites made from 251tex yarn increase as the twist factor increases, reaching a maximum of 135.59 MPa at 2420 (turns·m-1·tex-1/2) with the flexural modulus and failure strain stands at 7,28GPa and 2.69% respectively, at a volume fraction of 43%. However, beyond this point, the flexural strength decreases with further increases in the twist factor. The flexural properties results for the composites made of C193tex, C213tex, and C251tex yarns are consistent with other reported findings (Shah et al., 2014). These results highlight the importance of balancing yarn linear densities and twist factors for producing jute fibre-reinforced polymer composites with higher flexural properties suitable for structural applications. Each yarn linear density has an optimal twist factor for maximising flexural strength and modulus, with deviations from this optimal point resulting in reduced mechanical properties.

An analysis of variance (ANOVA) was conducted to evaluate the impact of the twist factor on the flexural properties of jute bio-epoxy composites. The properties analysed include flexural strength, modulus of elasticity, and elongation at break across various composites of yarn linear densities (C193, C213, and C251). The significance level was set at p<0.05p.

Table 8: Analysis of ANOVA Results on the Influence of Twist Factor on the Flexural Properties of Jute Bio-Epoxy Composites

Sources of variation	DF	Sum of Squares	Mean Square	F Value	Prob>F
JYC193-Flexural strength	3	1216.95085	405.65028	5.81282	0.00695*
JYC213-Flexural strength	3	2996.7951	998.9317	7.86194	0.0019*
JYC251-Flexural strength	3	5503.19138	1834.39713	32.7181	<0.0001*
JYC193-Flexural Modulus	3	5920044.764	1973348.255	2.75487	0.07654
JYC213-Flexural Modulus	3	1.07E+07	3573632.582	5.93384	0.0064*
JYC251-Flexural Modulus	3	2.59E+07	8632421.059	27.4343	<0.0001*
JYC193- Elongation at break	3	7.63778	2.54593	7.11476	0.00298*
JYC213-Elongation at break	3	11.95557	3.98519	8.96818	0.00102*
*JYC251-Elongation at break	3	22.4721	7.4907	68.88792	<0.0001*

*Signifiant diference

The ANOVA table provides a detailed statistical analysis of the impact of twist factors on the flexural properties of jute bio-epoxy composites produced from C193tex, C213tex, and C251tex. The analysis used a significance level of 0.05.

The results reveal that twist factors significantly influence the flexural properties across the different jute bio-epoxy composites. However, for the flexural modulus of C193tex, the p-value of 0.07654 indicates that the influence is not statistically significant. However, for the other composites, the p-values are generally below the 0.05 limit, suggesting that the twist factors result in statistically significant variations in flexural properties. The impact of twist factors is most noticeable in composites made from C251tex, emphasising the critical role of optimising both yarn linear density and twist factor to achieve structural composites. Overall, the analysis highlights the significant impact of twist factors on the flexural properties of jute fibre-reinforced polymer composite, regardless of the linear density of the composite yarn.

Effect of Twist Factor on the Impact Properties of Jute Bio-Epoxy Composites

Figure 11 shows the results of the impact tests carried out on the jute bio epoxy composites made from three different yarn linear densities: 193tex, 213tex, and 251tex, twisted into four different levels each to determine the composite's impact strength based on the yarn linear densities and twist factors using equation 4.

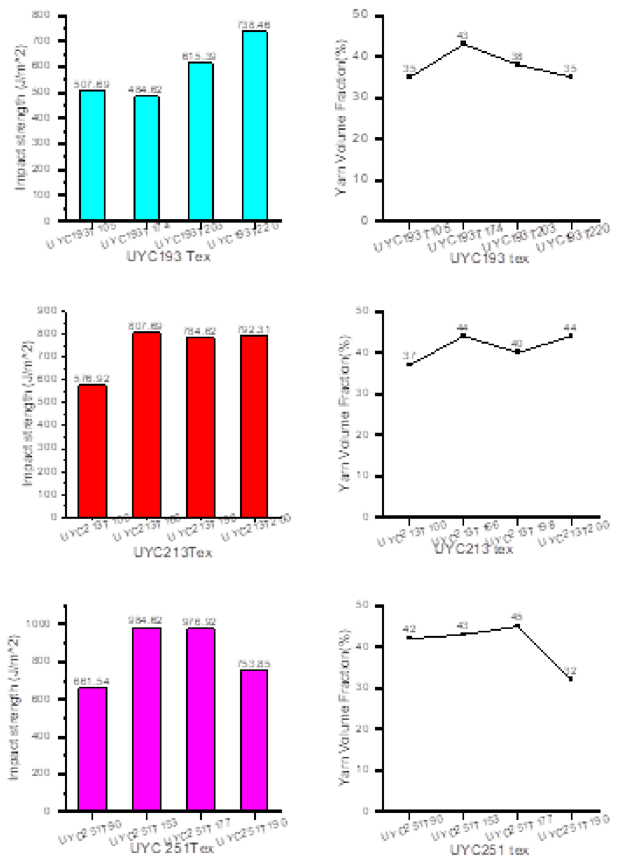

Figure 11: shows the statistical mean value of the composite impact strength according to the yarn linear densities and twist factor.

Figure 11 presents the average results from the impact strength tests conducted on jute bio-epoxy composites, with a detailed categorisation based on their linear densities and twist factors. The impact strength of a composite is a critical measure of its ability to withstand sudden, forceful impacts. The results indicate that the highest impact strength recorded for composites made from C193 tex was 738.46 J/m² at a 35% volume fraction. This peak performance was achieved with a twist factor of 3056 (turns·m-1·tex-1/2). Similarly, the C213 tex composite attained its maximum impact strength of 807.69 J/m² at a 44% volume fraction, with an optimal twist factor of 2420 (turns·m-1·tex-1/2). Notably, the C251T153 composite exhibited the highest impact strength of 984.62 J/m², also at a twist factor of 2420 (turns·m-1·tex-1/2) at a volume fraction of 43%.

These findings underscore a critical observation: the optimal twist factor for achieving maximum impact strength differs from that required for maximum tensile strength. This highlights the significant influence of twist factors, which can variably impact the development of different composite properties depending on the yarn's linear density. The data clearly show that the highest impact strengths are achieved through an optimal balance between the yarn's linear density and twist factor. This phenomenon occurs because the composite's impact strength is more dependent on the structural integrity of the yarn within the composite matrix rather than the strength of the individual fibres alone.

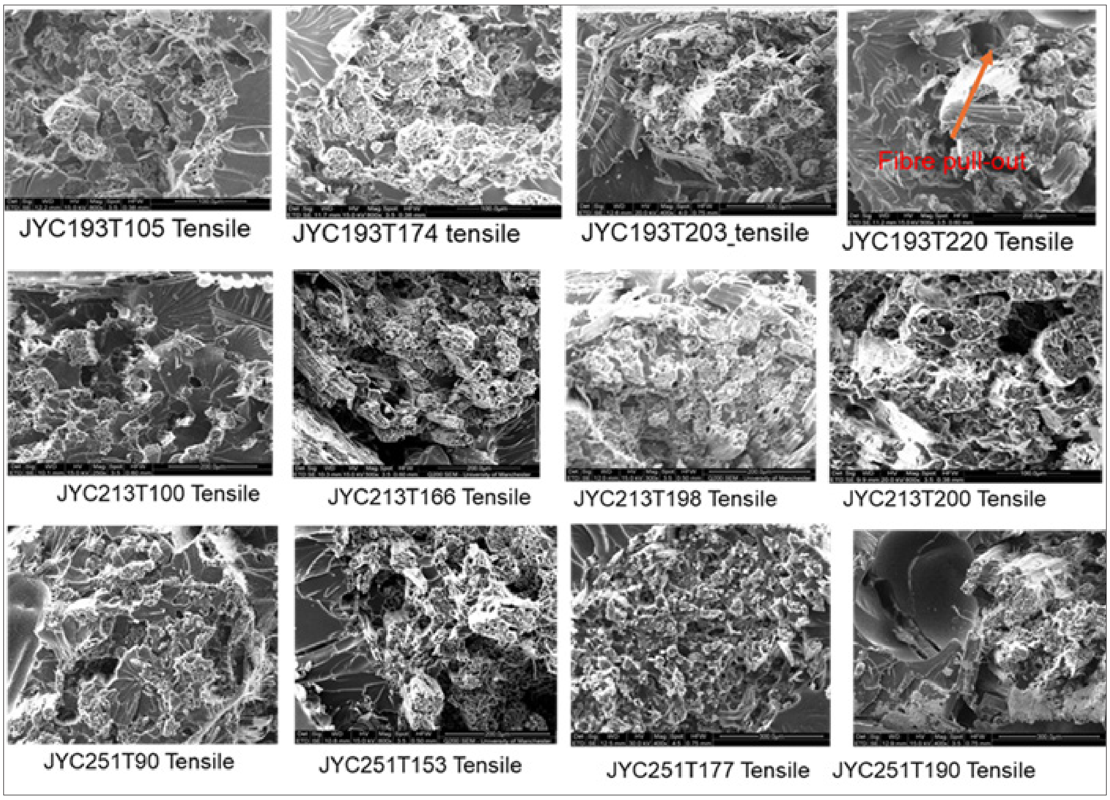

Figure 12: SEM images of the tensile fracture morphologies of the jute bio epoxy composites made from C193tex, C213tex, and C251tex.

Studying how jute bio-epoxy composites break when stretched provides important insights into the composites' strength, structure, and failure mechanisms. Figure 15 shows scanning electron microscope (SEM) images of different composite samples grouped by their linear density and twist factor pulled apart when subjected to axial tensile testing. Each image shows the material's microstructure after it has been stretched. The behaviour and failure mechanism of unidirectional laid composites pulled in the direction of the composite yarn depends on the fibre strength, matrix strength, yarn-matrix adhesion, yarn orientation within the composites, yarn packing density, and the method of the composites fabrication.

For composites made from 193 tex, we can see that C193T105 and C193T174 have a consistent microstructure with small cracks, indicating that the composite yarn has been effectively infused with the matrix. On the other hand, C193T203 and C193T220 show significant damage to the microstructure and clear signs of fibre pull-out, suggesting poor bonding between the fibres and the matrix. Similarly, the 213 tex composites show different characteristics: C213T100 has a relatively smooth fracture surface with minor microvoid coalescence, while C213T166 has a rougher surface, indicating more brittle fracture characteristics. C213T198 and C213T200 have highly irregular and textured surfaces with fibre pull-out, suggesting incomplete matrix penetration into all the fibres in the yarn (Wang et al., 2019).

For composites made from 251 tex, C251T90 shows a highly fractured surface with fine debris, indicating brittle fracture.

At the same time, C251T153 exhibits a rougher texture with larger debris, suggesting a combination of brittle and ductile fracture. Notably, C251T177 and C251T190 show noticeable fibre pull-out and matrix cracking, indicating inadequate resin impregnation and stress concentration within the composites.

The twist factor is crucial in determining the quality of the composites. The general observation indicates that composites with a low twist factor, regardless of linear density, have uniform microstructural surfaces. This uniformity suggests that the resin effectively penetrated the yarn during composite production, resulting in maximum tensile strength within this group. On the other hand, composites with an increased twist factor show poor matrix interaction with fibres in the yarn, resulting in a poor load distribution between the yarn and the matrix. The higher twist factor closes the gaps between fibres, preventing the matrix from fully covering them. As a result, less force is needed to pull out the fibres during tensile stress (Ma et al., 2016).

The fracture patterns of jute bio-epoxy composites with different yarn linear densities and twist factors highlight the critical role of the twist factor in creating high-performance composites. A low twist factor is linked to a low twist angle, which reduces fibre misalignment within the composites, maximising the effectiveness of fibre arrangement along the yarn axis. Understanding these fracture patterns is essential for optimising the production of high-performance composites (Pan, 2022; Shah et al., 2012; Testex, 2022).

Conclusion

This study investigated the impact of yarn linear density and twist factors on the mechanical properties of jute bio-epoxy composites, addressing the long-standing challenge of balancing these two parameters for optimal composite performance. Three jute yarn groups, C193tex, C213tex, and C251tex, were twisted at four different levels (1460, 2420, 2820, and 3056 turns per meter × √tex. The results show that adding twist to yarn makes it possible to be aligned in the load direction, but it also changes the yarn's physical and mechanical properties. Increasing the level of twist affects the yarn's cross-sectional areas, causing the fibres to become angled, which reduces the mechanical performance once the optimal twist level is surpassed. The study also highlighted that the highest yarn tensile properties do not necessarily translate into the highest tensile strength of the composites. Unlike yarn, which derives its strength from individual fibre properties, the mechanical properties of composites are also determined by the yarn-matrix interaction. The yarn imparts mechanical strength, while the matrix secures the yarns in position and distributes the load. Fibre orientation is critical in composite performance under tensile stress. As demonstrated, composites' highest tensile strength and modulus of elasticity were observed when the yarn was twisted between 1460 and 2420 turns per meter × √tex. The results emphasise that a lower twist factor is required to optimise yarn's linear density for high-performance composites, especially for higher yarn linear density. This balance promotes better matrix impregnation, as well as better alignment in the load direction, leading to better composite tensile properties. The study employed a one-way analysis of variance (ANOVA) to evaluate the significance of twist factors in influencing the jute composites' tensile, flexural, and impact properties. The findings showed statistical significance, with a p-value of less than 0.05, confirming the critical role of the twist factor in composite properties.

In conclusion, this research demonstrates the importance of selecting an appropriate twist factor that optimally balances yarn linear density prior to composite production. This selection enhances the overall mechanical properties of composites. Future studies will focus on theoretical modelling of the relationship between twist factors and yarn properties, aiming to improve the prediction of composite performance prior to production. This will allow for more precise optimisation of composite materials for structural applications.

Declaration

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Conflict of Interest

The authors declare that they have no known conflicting financial Interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary information

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Ethical Approval

Not applicable.

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