Citric Acid Modification of Jute Fibre: Comparative Study of Alkali, Citric Acid and Sodium-Hypophosphite Assisted Treatments

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Abstract*—Natural lignocellulosic fibres possess attractive sustainability and specific mechanical characteristics but exhibit hydrophilicity and limited interfacial compatibility with polymer matrices. Chemical surface modification is therefore widely employed to alter fibre morphology and surface chemistry. The present study investigates the comparative effects of sodium hydroxide (NaOH), citric acid (CA), and sodium-hypophosphite-assisted citric acid (CA/SHP) treatments on jute fibre. Untreated jute, 5% NaOH-treated jute, 5% citric-acid-treated jute and 5% CA/SHP-treated jute were characterised using field-emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectroscopy (EDS) and Fourier-transform infrared spectroscopy (FTIR). Particular emphasis was placed on EDS results expressed as both weight percentage and atomic percentage and on the resulting O/C ratios. Untreated jute exhibited 54.33 wt% C and 39.49 wt% O, whereas 5% CA treatment increased the oxygen content to 43.41 wt% and 37.02 at%. CA/SHP treatment produced the highest oxygen content, 43.83 wt% and 37.38 at%. The calculated atomic O/C ratio increased from approximately 0.547 for untreated jute to 0.594 and 0.603 for CA and CA/SHP treatments, respectively. NaOH treatment produced a smaller increase in atomic O/C but caused a substantial reduction in Si and Ca, indicating removal of surface-associated constituents. FESEM observations revealed increased fibrillation, longitudinal grooves and surface irregularities following chemical modification. FTIR analysis showed characteristic hydroxyl, C–H, carbonyl-related and C–O absorption bands. The combined EDS, FESEM and FTIR results indicate that citric acid produces significant oxygen-rich surface modification, with CA/SHP producing the strongest oxygen enrichment among the investigated conditions. The findings provide supporting evidence for citric-acid-induced chemical modification and potential improvement in fibre–matrix interaction.

***Index Terms*—jute fibre; citric acid; sodium hydroxide; sodium hypophosphite; EDS; atomic percentage; esterification; FTIR; FESEM; natural fibre composite**

I. INTRODUCTION

The increasing demand for sustainable materials has accelerated research into natural fibre-reinforced polymer composites. Natural fibres such as jute, flax, hemp, sisal and coir are attractive reinforcement materials because of their renewable origin, low density, relatively low cost and favourable specific properties. Jute is particularly important because of its high availability and established textile-processing infrastructure [1–4].

Despite these advantages, the incorporation of jute into polymer composites presents several challenges. Jute is a lignocellulosic material containing cellulose, hemicellulose, lignin and smaller amounts of pectin, waxes and inorganic constituents. The hydroxyl-rich structure of cellulose and other polysaccharides gives the fibre a hydrophilic character. This can result in moisture absorption, dimensional instability and inadequate compatibility with relatively hydrophobic polymer matrices [5–8].

Surface modification is therefore an important approach for improving natural fibre performance. Alkali treatment is among the most widely used chemical treatments because NaOH can remove surface impurities, waxes and portions of non-cellulosic constituents while producing fibrillation and increasing surface roughness [5,9–11]. Such morphological changes can increase mechanical interlocking between the fibre and polymer matrix.

Recent studies have demonstrated that chemical or physical activation of jute can modify surface morphology and chemistry and subsequently influence fibre–matrix interaction. For example, surface activation of jute fibres has been shown to increase surface roughness and improve adhesion in polyester-based systems [12]. Similarly, recent investigations of chemically modified jute/polyester composites demonstrate the importance of surface treatment in controlling interfacial properties [13,14].

Organic acids provide an alternative route for modifying lignocellulosic fibres. Citric acid (CA) contains three carboxyl groups and can interact with hydroxyl groups in cellulose. Under appropriate reaction conditions, esterification between carboxyl groups of citric acid and hydroxyl groups of cellulose can occur. Sodium hypophosphite (SHP) is widely investigated as a catalyst/promoter for citric-acid-induced crosslinking of cellulose-based materials. In a recent study of ramie fibre, CA/SHP treatment was associated with FTIR evidence of esterification and changes in fibre properties [15].

The proposed simplified reaction can be represented as:

The reaction represents the formation of a cellulose ester through interaction between a cellulose hydroxyl group and a citric-acid carboxyl group. In practice, the chemistry can be more complex because citric acid contains multiple carboxyl groups and can participate in intra- and intermolecular reactions. An important analytical issue is distinguishing elemental oxygen enrichment from direct evidence of esterification. EDS determines elemental composition but does not identify the chemical bonding environment of oxygen. FTIR, on the other hand, can provide functional-group information, particularly in the carbonyl and C–O regions.

Therefore, combining EDS with FTIR and morphological analysis provides a more reliable assessment of chemical surface modification. The objective of the present investigation was therefore to compare untreated jute with 5% NaOH-, 5% CA- and 5% CA/SHP-treated jute using FESEM, EDS and FTIR. Particular attention was given to both EDS weight percentage and atomic percentage, and to the relationship between oxygen enrichment and possible citric-acid-induced esterification.

II. MATERIALS AND METHODS

2.1 Materials

Jute fibre was used as the lignocellulosic reinforcement. Sodium hydroxide, citric acid and sodium hypophosphite were used for chemical modification.

Four fibre conditions were considered:

- Pl: Plain/untreated jute fibre
- Na: 5% NaOH-treated jute fibre
- CT-5: Alkali treated jute with 5% citric-acid
- SCT-5: Alkali treated jute with 5% citric-acid/sodium-hypophosphite

The comparative analysis was restricted to a common 5% treatment concentration to facilitate direct comparison of the different chemical treatments.

2.2 Chemical treatment of jute fibre

The woven jute fabric was subjected to chemical treatment using the experimental procedure adopted in the study. All treatments were performed under the same general experimental conditions; temperature and treatment duration were not treated as independent variables. Woven jute fabric was cut into 300x300 mm pieces. It was washed thoroughly well with water to remove dirt, dust from the surface. Fabric was dried to room temperature.

This was labelled as Pl. Similar fabric was soaked in 5% NaOH solution for 3 hrs. Fabric was then washed with water and neutralised. Further it was washed with water and dried at room temperature. This was labelled as Na. Alkali treated jute fabric of same size was then treated with 5% Citric acid for 3 hrs.at room temperature and further washed with water and dried at room temperature. This was labelled as CT-5. Alkali treated jute fabric was treated with 5% Citric acid assisted with Sodium Hypophosphite as a catalyst for 3 hrs. This was labelled as SCT-5.

Following treatment, the fibres were washed to remove residual chemicals and subsequently dried before characterisation.

For the CA/SHP system, sodium hypophosphite was incorporated as a catalyst/promoter for citric-acid-mediated modification. The process is represented in Figure 1.

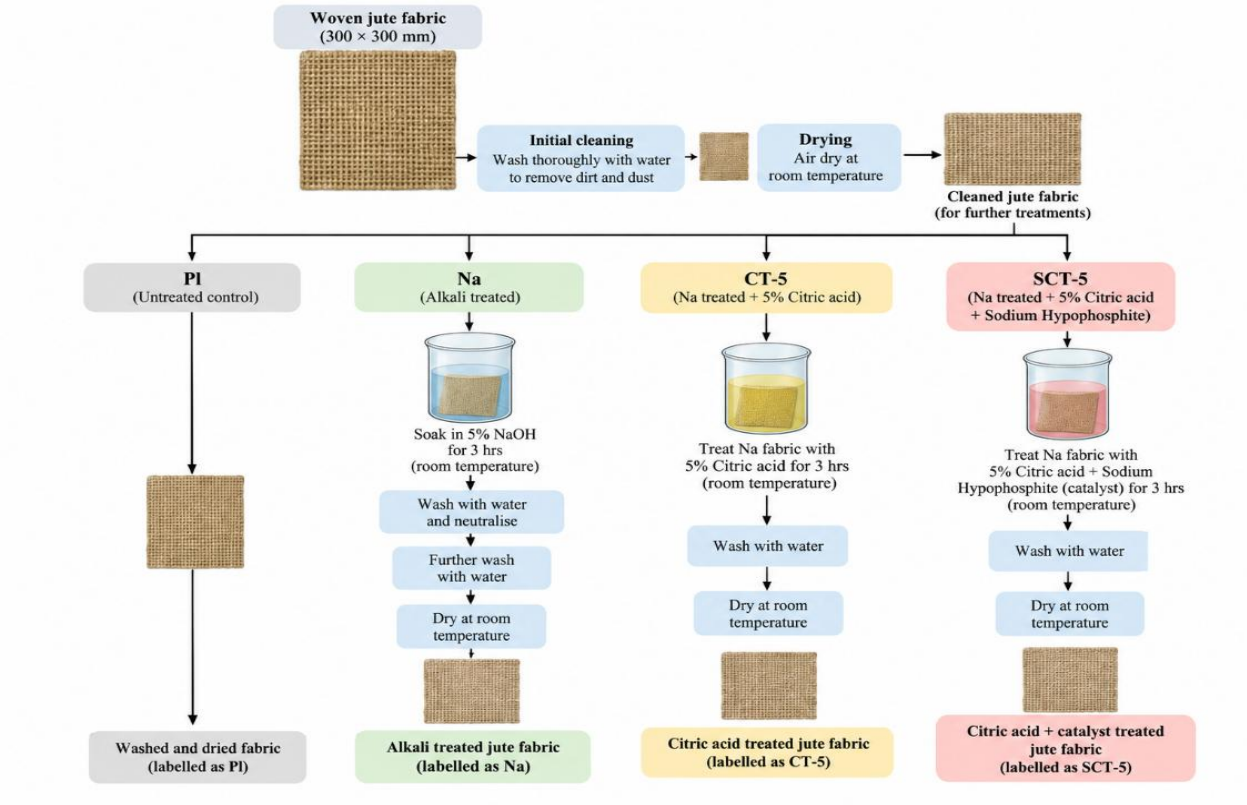

Figure 1. Schematic representation of the chemical treatment of jute fibre.

III. CHARACTERISATION TECHNIQUES

3.1 FESEM analysis

FESEM was used to investigate the morphological changes produced by chemical treatment. Particular attention was given to surface deposits, grooves, fibrillation, roughness, exposed fibrillar regions and surface irregularities.

3.2 EDS analysis

EDS was used to determine the elemental composition of the fibre surface. Carbon, oxygen, silicon and calcium were detected in the investigated samples.

Both weight percentage (wt%) and atomic percentage (at%) were considered.

The weight-based oxygen-to-carbon ratio was calculated as:

$$(O/C)_{wt} = \frac{O(wt\%)}{C(wt\%)}$$

For comparison based on the relative number of atoms, the atomic O/C ratio was calculated from the atomic percentages:

$$(O/C)_{atomic} = \frac{O(at\%)}{C(at\%)}$$

The atomic O/C ratio was used as the principal EDS parameter for evaluating relative oxygen enrichment.

3.3 FTIR spectroscopy

FTIR spectroscopy was performed to identify changes in the characteristic functional groups of the jute fibre. The principal absorption regions considered were:

- approximately 3315 cm^{-1} — O–H stretching
- approximately 2896 cm^{-1} — C–H stretching
- approximately 1730 cm^{-1} — carbonyl-related C=O stretching
- approximately 1437 cm^{-1} — CH_2 deformation
- approximately 1030 cm^{-1} — C–O stretching.

The carbonyl region was particularly important in evaluating the possibility of citric-acid-induced esterification.

IV. RESULTS AND DISCUSSION

4.1 EDS elemental composition

The EDS elemental composition obtained for the four investigated fibre conditions is presented in Table 1.

Table 1. EDS elemental composition of untreated and chemically modified jute fibre

Sample	C (wt%)	O (wt%)	Si (wt%)	Ca (wt%)	C (at%)	O (at%)	Si (at%)	Ca (at%)
Pl	54.33	39.49	3.92	2.26	62.93	34.44	1.94	0.78
Na	56.21	41.79	1.23	0.77	63.67	35.54	0.42	0.37
CT-5	54.91	43.41	1.35	0.33	62.37	37.02	0.46	0.16
SCT-5	54.60	43.83	1.12	0.44	62.02	37.38	0.38	0.21

The untreated jute fibre contained 54.33 wt% carbon and 39.49 wt% oxygen. Following NaOH treatment, the oxygen content increased to 41.79 wt%. A more pronounced oxygen enrichment was observed after citric-acid treatment, with 43.41 wt% O for 5% CA. The highest oxygen concentration, 43.83 wt%, was obtained for CA/SHP.

A similar trend was obtained when the results were expressed as atomic percentage. Oxygen increased from 34.44 at% in untreated jute to 35.54 at% after NaOH treatment, 37.02 at% after CA treatment and 37.38 at% after CA/SHP treatment.

This agreement between weight and atomic percentages is significant because it demonstrates that the observed oxygen enrichment is not restricted to a particular method of expressing EDS composition.

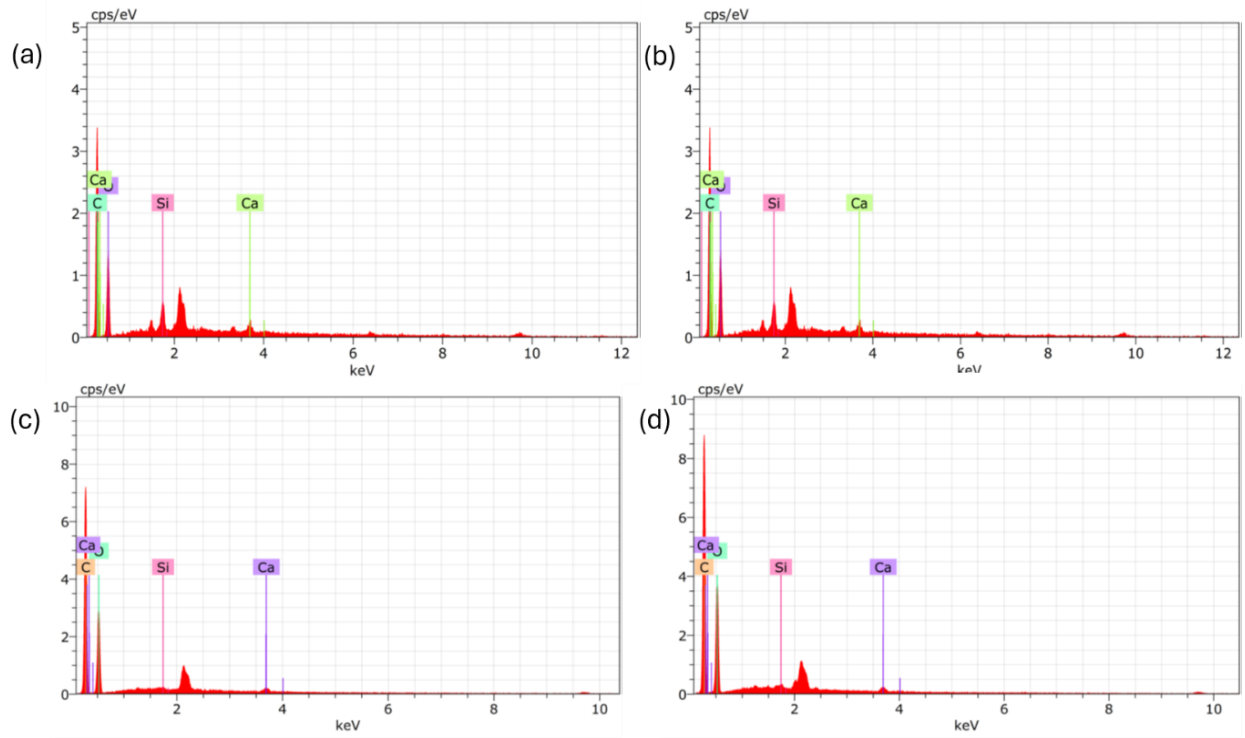

Figure 2. EDS spectra of (a) plain jute, (b) 5% NaOH-treated jute, (c) 5% CA-treated jute and (d) 5% CA/SHP-treated jute.

4.2 Comparison of atomic and weight-based O/C ratios

The calculated O/C ratios are shown in Table 2.

Table 2. Comparison of oxygen-to-carbon ratios

Sample	O/C weight ratio	O/C atomic ratio	Increase in atomic O/C vs. plain
Plain	0.727	0.547	—
5% NaOH	0.743	0.558	~2.1%
5% CA	0.791	0.594	~8.6%
5% CA/SHP	0.803	0.603	~10.3%

Both forms of calculation exhibit the same overall trend:
Plain < NaOH < CA < CA/SHP
The atomic O/C ratio increased from approximately 0.547 for untreated jute to 0.594 after CA treatment and 0.603 after CA/SHP treatment.

The approximately 8.6% increase following CA treatment and approximately 10.3% increase following CA/SHP treatment indicate an oxygen-enriched fibre surface.

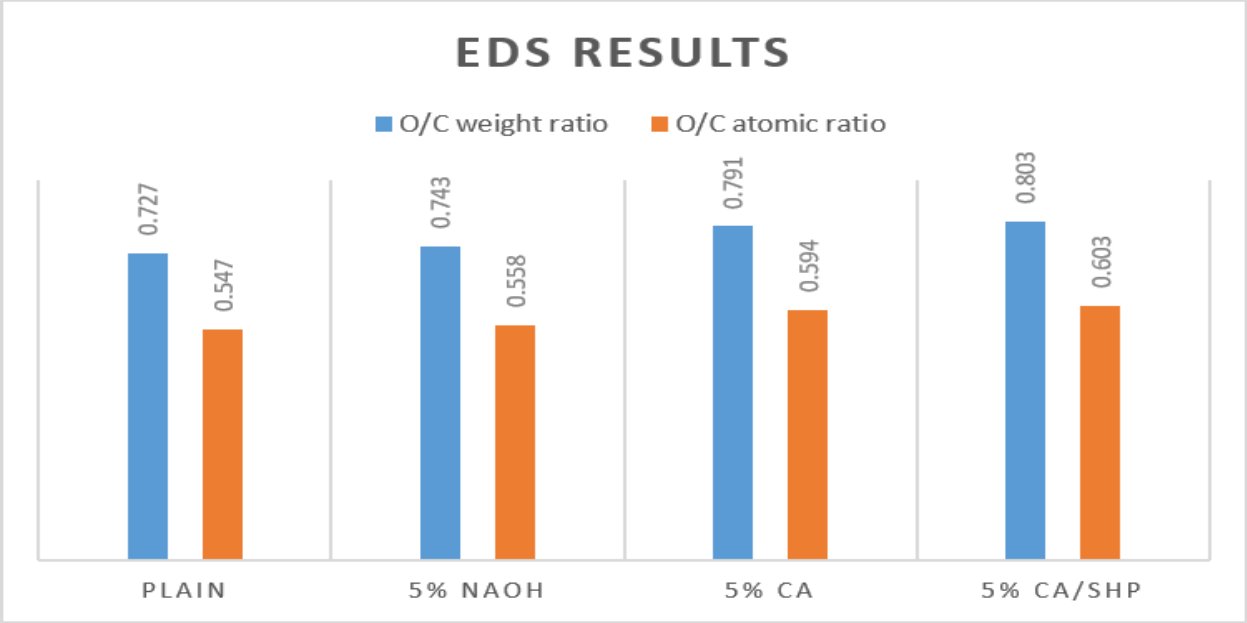

Figure 3. Comparison of O/C ratios calculated from EDS weight percentage and atomic percentage.

4.3 Changes in carbon and oxygen composition
The carbon content remained relatively similar across the four conditions, ranging from 54.33 to 56.21 wt%. In contrast, oxygen showed a more distinct treatment-dependent variation.
The 5% CA/SHP sample showed the highest oxygen content in both representations:
43.83 wt% O and 37.38 at% O. The corresponding carbon concentration was 54.60 wt% and 62.02 at%. The increase in oxygen relative to carbon is therefore better expressed by the O/C ratio than by considering oxygen concentration alone.

The results indicate that citric-acid treatment produces a more oxygen-rich surface than untreated and NaOH-treated jute. Similar emphasis on surface chemical modification and oxygen-containing functionality has been reported in recent studies of treated natural fibres [12,16–18]. Surface activation of jute can increase the availability of oxygen-containing functional groups and alter surface characteristics relevant to matrix interaction [12].

4.4 Effect of NaOH treatment
The NaOH treatment resulted in an increase in oxygen from 39.49 to 41.79 wt% and from 34.44 to 35.54 at%. However, the atomic O/C ratio increased only from approximately 0.547 to 0.558.
A much more pronounced change was observed for the minor elements. Silicon decreased from 3.92 to 1.23 wt%, while calcium decreased from 2.26 to 0.77 wt%.

The combined Si + Ca concentration therefore decreased from 6.18wt% in untreated jute to 2.00wt% after NaOH treatment. This represents a substantial reduction in surface-associated Si and Ca.
The result is consistent with the commonly reported role of alkaline treatment in removing surface impurities and portions of non-cellulosic constituents and in producing fibrillation [5,9,10]. Recent reviews identify alkali treatment as one of the most extensively investigated approaches for modifying natural fibre surfaces [6,7,16].

4.5 Effect of citric acid treatment

The 5% CA-treated fibre showed a greater oxygen enrichment than the NaOH-treated fibre. The oxygen concentration increased to 43.41 wt% and 37.02 at% while the atomic O/C ratio increased to 0.594. This represents approximately an 8.6% increase in atomic O/C relative to untreated jute.

The increase is consistent with modification involving oxygen-containing functional groups. Citric acid possesses multiple carboxyl groups and can interact with the hydroxyl-rich cellulose structure. Under suitable conditions, esterification can occur between cellulose hydroxyl groups and citric-acid carboxyl groups.

However, the increased O/C ratio should not be interpreted as direct quantitative proof of esterification. EDS provides elemental rather than molecular-bond information.

4.6 Effect of sodium-hypophosphite-assisted citric acid treatment

The CA/SHP-treated fibre exhibited the highest oxygen concentration and highest atomic O/C ratio compared with untreated jute.

$O/C_{atomic}: 0.547 \rightarrow 0.603$

This corresponds to an increase of approximately 10.3%.

The weight-based O/C ratio similarly increased from 0.727 to 0.803.

The CA/SHP result is particularly relevant because SHP has been investigated as a catalyst/promoter for citric-acid crosslinking of cellulose-based materials. A recent study on ramie fibres reported FTIR evidence consistent with esterification following CA/SHP treatment [15]. Thus, the present EDS results provide complementary elemental evidence of the oxygen-rich surface modification associated with the CA/SHP system.

The present results indicate that the O/C increase indicates oxygen enrichment on the surface of the fiber.

4.7 Silicon and calcium removal

An additional important observation is the reduction in Si and Ca following treatment.

Table 3. Reduction of Si and Ca

Sample	Si + Ca (wt%)	Reduction relative to plain
Plain	6.18	—
5% NaOH	2.00	67.6%
5% CA	1.68	72.8%
5% CA/SHP	1.56	74.8%

The combined Si + Ca content decreased by approximately 67.6%, 72.8% and 74.8% after NaOH, CA and CA/SHP treatment, respectively.

This reduction provides additional evidence that chemical treatment altered the outer fibre surface.

It is particularly important because surface deposits and non-cellulosic materials can act as barriers to fibre–matrix interaction. Removal of such material can expose fibrillar regions and increase the effective interaction area [6,7].

4.8 FESEM morphological analysis

The EDS findings are supported by the morphological observations obtained from FESEM.

4.8.1 Plain jute

The FESEM images of untreated jute fibre show a relatively heterogeneous smooth surface with longitudinal grooves, fibrillar structures and surface-associated deposits. Several discrete particulate deposits are also visible on and around the fibre surface. These features are characteristic of the complex, multilayered structure of untreated lignocellulosic fibres.

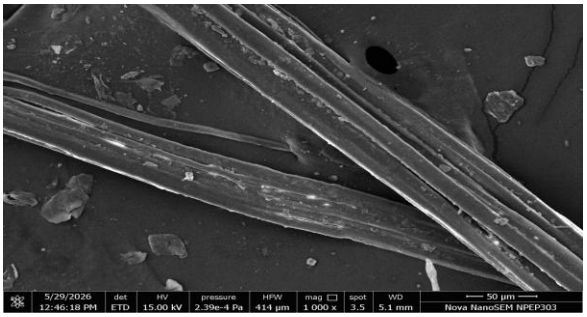

Figure 4. FESEM micrograph of untreated jute fibre at 1000×.

4.8.2 5% NaOH-treated jute

Following NaOH treatment, the fibre surface exhibited greater fibrillation and more clearly developed longitudinal channels. The modification indicates disruption/removal of some superficial material and exposure of the underlying fibrillar structure.

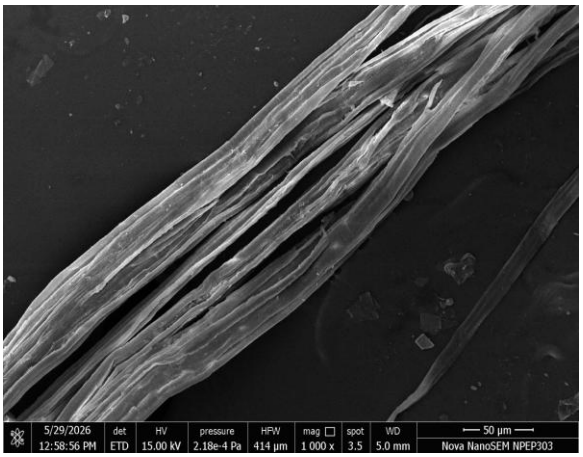

Figure 5. FESEM micrograph of 5% NaOH-treated jute fibre at 1000×.

Such changes are consistent with the established role of alkaline treatment in modifying the surface morphology of lignocellulosic fibres [5,6,9].

4.8.3 5% CA-treated jute

The CA-treated fibre showed defined longitudinal grooves and surface irregularities while retaining its overall fibrillar architecture.

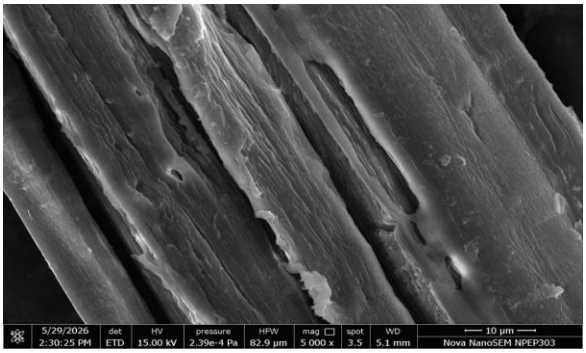

Figure 6. FESEM micrograph of 5% CA-treated jute fibre at 5000×.

The development of surface irregularities can potentially increase mechanical interlocking with a polymer matrix.

4.8.4 5% CA/SHP-treated jute

The CA/SHP-treated fibre exhibited a modified fibrillar surface with longitudinal grooves and localized surface irregularities.

Recent studies on jute/polyester systems have similarly demonstrated that modification of the fibre surface can alter roughness and interfacial behaviour [12–14,19].

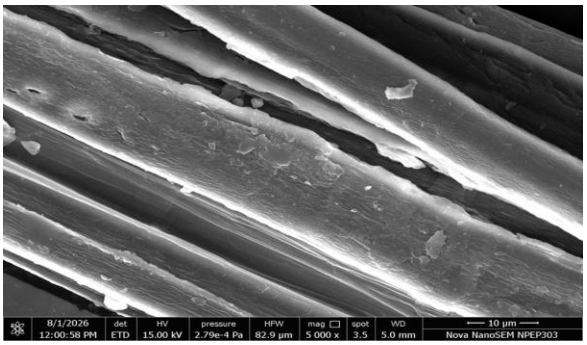

Figure 7. FESEM micrograph of 5% CA/SHP-treated jute fibre at 5000×.

4.9 FTIR analysis

The FTIR spectrum of the jute fibre showed the characteristic absorption bands associated with lignocellulosic constituents.

The broad absorption around 3315 cm^{-1} is attributed mainly to O–H stretching vibrations. The strong hydroxyl contribution reflects the hydrophilic nature of cellulose and other polysaccharides.

The absorption around 2896 cm^{-1} is associated with C–H stretching vibrations of cellulose and hemicellulose.

The band near 1730 cm^{-1} is associated with carbonyl-containing groups. In lignocellulosic materials, this region can include contributions from carbonyl and ester/carboxyl functionalities associated particularly with hemicellulosic constituents. Consequently, changes in this band after CA treatment are relevant to chemical modification but should not be interpreted alone as conclusive evidence of esterification.

The band around 1437 cm^{-1} can be assigned to CH_2 deformation in cellulose, while the strong absorption around 1030 cm^{-1} corresponds predominantly to C–O stretching vibrations.

Wavenumber (cm^{-1})	Assignment	Interpretation for your samples
3315	O–H stretching	Broad absorption associated with hydroxyl groups in cellulose, hemicellulose and absorbed moisture. Changes may reflect altered hydrogen bonding, moisture content or hydroxyl-group chemistry.

2896	Aliphatic C–H stretching	Associated with carbohydrate and other organic structures in jute. Changes are not a specific indicator of esterification.
1730	C=O stretching	Important for assessing citric-acid modification. An ester-related contribution may occur here, but native hemicellulose and other carbonyl-containing constituents can also contribute.
1437	CH_2 deformation	Associated mainly with cellulose-related structural vibrations. Changes may indicate modifications to the lignocellulosic structure.
1030	C–O stretching	Strong band associated with cellulose and other polysaccharides. It may also include contributions from ester-related C–O vibrations, but is not specific to ester formation.

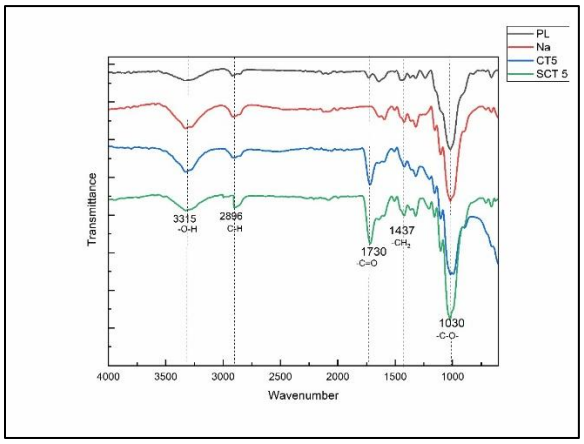

Figure 8. FTIR spectra of (a) plain jute (PL), (b) 5% NaOH-treated jute (Na), (c) 5% CA-treated jute (CT5) and (d) 5% CA/SHP-treated jute (SCT 5).

Recent studies of treated jute fibres have similarly used FTIR changes in carbonyl, hydroxyl and C–O-containing regions as evidence of changes in surface chemistry [12,20]. In a CA/SHP-modified cellulosic fibre system, FTIR evidence has also been used to support esterification [15].

4.10 Proposed mechanism of citric-acid modification

The proposed mechanism involves interaction between the hydroxyl groups of cellulose and the carboxyl groups of citric acid.

Initially, citric acid interacts with the hydroxyl-rich fibre surface. Under suitable activation conditions and in the presence of SHP, esterification can occur, resulting in cellulose–citrate ester linkages.

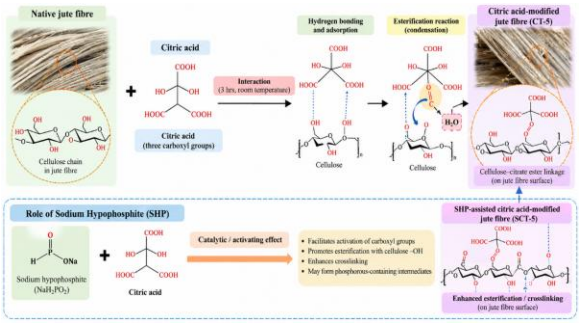

Figure 9. Proposed mechanism of citric-acid-induced modification/esterification of cellulose in jute fibre.

The simplified reaction can be represented as:

$$\text{Cell} - \text{OH} + \text{HOOC} - \text{R} - \text{COOH} \rightarrow \text{Cell} - \text{OCO} - \text{R} - \text{COOH} + \text{H}_2\text{O}$$

with SHP acting as a catalyst/promoter.

Because citric acid contains more than one carboxyl group, further reaction may produce crosslinking between cellulose chains under suitable conditions.

This interpretation is consistent with research demonstrating CA/SHP-mediated modification of cellulose-based fibres and FTIR evidence associated with esterification [15].

4.11 Overall correlation of FESEM, EDS and FTIR

The integrated characterisation therefore demonstrates that the treatments produce different modification mechanisms.

NaOH predominantly produces surface cleaning and fibrillation, whereas CA produces a more pronounced oxygen-rich chemical modification.

Table 4. Integrated interpretation of characterisation results

Treatment	EDS observation	FESEM observation	FTIR interpretation	Overall interpretation
Plain	Lowest O/C	Heterogeneous surface	Native lignocellulosic groups	Untreated reference
5% NaOH	Strong Si/Ca reduction; small O/C increase	Fibrillation/roughness	Modification of native surface groups	Mainly surface cleaning and fibrillation
5% CA	Increased O and O/C	Modified grooves/roughness	Changes in oxygen/carbonyl-related functionality	Chemical and morphological modification
5% CA/SHP	Highest O and O/C; lowest Si+Ca	Modified fibrillar surface	Changes consistent with CA-mediated functionality	Strongest oxygen-rich surface modification

CA/SHP exhibits the strongest oxygen enrichment and is therefore particularly promising for further investigation of citric-acid-induced esterification.

V. IMPLICATIONS FOR JUTE–POLYESTER COMPOSITES

Surface modification of jute is particularly relevant to polyester composites because the fibre surface influences wetting, mechanical interlocking and interfacial stress transfer.

Untreated jute possesses a hydrophilic, hydroxyl-rich surface, whereas polyester resin is comparatively less polar. This chemical difference can limit interfacial adhesion [5–8]. Modification of the fibre surface can change surface roughness and chemical functionality and thereby potentially improve fibre–matrix interaction.

Recent work on jute/polyester systems has demonstrated that surface activation can influence fibre–matrix bonding, while chemical modification of jute has been investigated as a route to improve composite performance [12–14]. However, the effect is treatment-dependent: excessive modification can damage fibre structure, while insufficient modification may not adequately alter the interface [6,7].

In the present study, CA/SHP produced the highest atomic O/C ratio and the lowest combined Si + Ca concentration. The FESEM results also indicated a modified fibrillar surface. These characteristics suggest a potentially favourable surface for subsequent jute–polyester interaction.

Nevertheless, because composite tensile, flexural and water-absorption measurements were not part of the present fibre-characterisation study, an improvement in composite mechanical properties cannot be claimed directly.

VI. SCIENTIFIC SIGNIFICANCE OF THE EDS RESULTS

The EDS results provide three complementary observations:

1. Oxygen enrichment

$34.44\ \text{at\%} \rightarrow 37.02\ \text{at\%} \rightarrow 37.38\ \text{at\%}$

for plain, CA and CA/SHP fibres.

2. Increase in atomic O/C

$0.547 \rightarrow 0.594 \rightarrow 0.603$

3. Reduction of surface-associated Si and Ca

$6.18 \rightarrow 1.68 \rightarrow 1.56\ \text{wt\%}$

for combined Si + Ca after CA and CA/SHP treatments.

The simultaneous occurrence of these changes provides stronger evidence of surface modification than any single elemental parameter alone.

VII. LIMITATIONS

A limitation of the present investigation is that EDS provides elemental composition but does not identify the chemical state of carbon or oxygen. Therefore, an increase in O/C cannot independently establish the formation of ester bonds.

Similarly, the FTIR carbonyl band near 1730 cm^{-1} may contain contributions from native lignocellulosic components, particularly hemicellulose-derived ester/carboxyl groups. Therefore, esterification should

be established using multiple complementary observations.

For a more quantitative evaluation, future work should include:

- degree of esterification;
- XPS for surface chemical-state analysis;
- XRD for crystallinity;
- TGA/DTG for thermal stability;
- contact-angle analysis;
- moisture/water absorption;
- tensile and flexural testing of jute–polyester laminates;
- fibre pull-out or interfacial shear testing.

VIII. CONCLUSIONS

The present investigation compared untreated jute with 5% NaOH-, 5% citric-acid- and 5% CA/SHP-treated fibres using FESEM, EDS and FTIR.

1. EDS analysis demonstrated an increase in oxygen concentration following chemical modification.
2. The oxygen concentration increased from 39.49 wt% and 34.44 at% for untreated jute to 43.41 wt% and 37.02 at% for 5% CA-treated jute.
3. CA/SHP treatment produced the highest oxygen concentration, 43.83 wt% and 37.38 at%.
4. The atomic O/C ratio increased from approximately 0.547 for untreated jute to 0.594 after CA treatment and 0.603 after CA/SHP treatment.
5. NaOH treatment produced a relatively small increase in O/C but substantially reduced Si and Ca, indicating effective removal of surface-associated constituents.
6. FESEM revealed increased fibrillation, longitudinal grooves and surface irregularities following treatment.
7. FTIR showed characteristic O–H, C–H, carbonyl-related and C–O absorption bands, with the carbonyl region being particularly relevant to CA-induced chemical modification.
8. The combined EDS, FESEM and FTIR results provide strong evidence of citric-acid-induced surface modification of jute fibre, with CA/SHP producing the strongest oxygen-rich surface signature.
9. The results are consistent with possible esterification between citric acid and cellulose hydroxyl groups, particularly in the presence of SHP; however, EDS and FTIR alone cannot quantitatively establish the degree of esterification.
10. The modified surface characteristics indicate potential for improved interaction with polyester resin. Direct composite mechanical, interfacial and moisture-absorption tests are required to establish the practical effect of the treatments on jute–polyester laminate performance.

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