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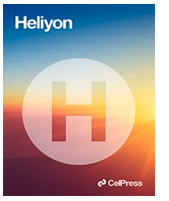

Optimization of the novel jute retting process to enhance the fiber quality for textile applications

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ABSTRACT

This study introduces an innovative chemical retting approach, systematically optimized via Grey relational analysis, to achieve jute fibers that exhibit desirable characteristics of softness, high tensile strength, and suitability for spinning, with a particular focus on their application in the apparel industry. In this study, the effect of alkali treatment (alkali concentration, temperature and duration of retting) on jute fiber's chemical composition and mechanical characteristics was investigated. Jute fibers were treated at three concentrations (5 %, 10 %, 15 %) of alkali, at three different temperature (30 °C, 60 °C, & 90 °C) and for three different retting duration (12 h, 24 h, & 36 h). The surface morphology and crystallinity of fibers were analyzed using optical microscopy, X-ray diffraction (XRD) and Fourier transform infrared (FTIR) spectroscopy. The fiber linear density and mechanical characteristics were also tested. The multi-response optimization of all the factors and the responses was investigated using the Grey relational analysis. The results showed that the fiber surface morphology and crystallinity increase with an increase in alkali concentration, retting time, and temperature. Chemical retting treatment also improved the fiber linear density and tensile strength. The finest fibers which were obtained in this research had a linear density of 2.18 Tex with a tenacity of 53.02 cN/tex and elongation of 4.54 %. The spinnable jute fibers were achieved after this treatment with excellent characteristics.

1. Introduction

The "golden" jute (Corchoru Olitorius L. and Corchorus Capsulris L.) is a plant based renewable natural fiber [1]. Countries in the southeast Asia such as India, Bangladesh, Nepal, China, Malaysia, and Thailand are the major producers of jute fibers [2]. Among the available natural cellulosic fibers, jute is the second most abundant fiber after cotton [3]. Jute fibers are mainly composed of cellulose (58–63 %), hemicellulose (20–24 %), lignin (12–15 %), and small quantities of pectin, wax, and water [4,5]. Jute fibers consist of several cellulose based, crystalline microfibrils. These small cellulosic based units are cemented with the bark/stem by hemicellulose, pectin, lignin, and gummy matter [2,6]. The cellulose-based fibrils are extracted from the non-fibrous woody part by removing lignin, natural oils, pectin, and waxy substances. This process of separation and dissolution of the nonfibrous part from the fibrous part is called "retting" [7].

In the typical retting process, the jute bundles are submerged in slow flowing water for about 14–28 days [8]. The physicochemical and microbiological changes in the retting water degrade the pectin, lignin, and hemicellulose in the jute stem [9]. The retting process directly influences the quality of the extracted fibers and their competitiveness in the market [10–12].

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The conventional water retting process requires a huge amount of water, is labor intensive, and causes environmental pollution [13]. To overcome the problems of the conventional retting process, several researchers investigated different retting processes. In the ribbon retting process, the barks were removed from the jute plant, and the bundles of barks were immersed in water for the retting process. The ribbon retting process decreases water consumption and environmental pollution and increases fiber quality [14].

A powerful pectinolytic bacteria inoculum was added to speed up the ribbon retting process [15]. But the ribbon retting process still requires 4–5 days. The retting process was speed up by the combined action of the different bacteria with the ribbon retting technique [16–18].

Water retting is one of the oldest methods for separating jute fibers. It involves the immersion of harvested jute stems in water, allowing the action of natural microorganisms to degrade the pectin and other compounds holding the fibers. Several studies have investigated the water retting process to understand its mechanisms and optimize its efficiency. Blair et al. analyzed the microbial communities involved in water retting and found that specific bacteria and fungi play crucial roles in breaking down the pectin, providing insights for potential process improvements [19]. However, Lee et al. concluded that water retting is time consuming, ranging from 10 to 30 days, and it may result in uneven retting and water pollution due to microbial activity [20].

Chemical retting has emerged as an alternative to traditional water retting, offering shorter processing times and better control over fiber quality. Various chemicals, such as sodium hydroxide (NaOH) and hydrogen peroxide (H_2O_2), have been used as effective retting agents. Lee et al. compared different chemical retting methods and found that a treatment with NaOH exhibited the most promising results in terms of fiber quality and retting efficiency [20]. Tahir et al. reported that chemical retting can be completed within 2–3 h, significantly reducing the processing time compared to water retting [10]. Moreover, Sisti et al. reported that chemical retting resulted into consistent and uniform retting, leading to improved fiber strength and fineness [21].

Comparative analysis of water retting and chemical retting to evaluate their respective merits has been reported in several studies. Summerscales et al. compared the mechanical properties of jute fibers processed through both methods and found that the fiber obtained from chemical retting had higher tensile strength and elongation that water retted fibers. Additionally, environmental impact assessments have been carried out to determine the ecological implications of each retting process [22]. Sadrmanesh et al. reported that chemical retting generates fewer greenhouse gas emissions and wastewater pollutants compared to water retting, making it an environment friendly option [23].

In the literature, the use of chemicals, enzymes, and bacteria is reported for the removal of lignin and other gummy matters to enhance the characteristics of the fibers through retting process [24–30]. However, these treatment processes expensive and consumes a lot of resource.

In this research, a novel chemical retting method is proposed and optimized (through Grey relational analysis) for the obtaining soft, strong, and spinnable jute fibers for apparel applications. The fibers were directly extracted from the stem. The extracted fibers can be effectively used for yarn manufacturing without further chemical, microbial or enzymatic treatments. The proposed treatment method is a sustainable approach that produces high quality fibers with lesser use of water, & time.

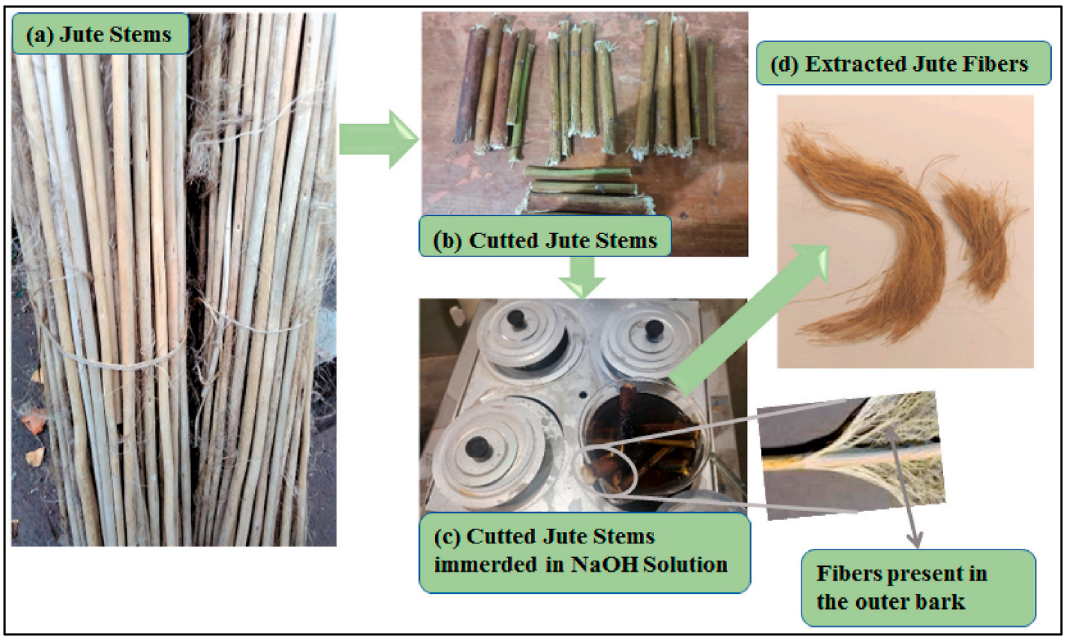

Fig. 1. Chemical retting of jute stems.

2. Materials and methods

2.1. Materials

Sodium Hydroxide (NaOH), Acetic Acid (CH_3COOH) reagent grade, and Sodium Chlorite ($NaClO_2$) technical grade 80 %, was purchased from Daejung Chemicals Reagents, Korea. Jute plant stems were provided by "Thal Jute Mills, Pakistan".

2.2. Method

The long stems of jute plants were trimmed to a length of 6 inches. The extraction of jute fibers from the jute stems was carried out using the chemical retting technique, as illustrated in Fig. 1.

For retting, small bundles of jute stem were immersed in sodium hydroxide (NaOH) solution with varying concentrations, temperatures, and durations. Preliminary trials were conducted at three different concentrations, three temperatures, and for three durations of time. It was observed that below the selected concentration, temperature, and soaking duration level, retting process was not carried out. The fibers are not extracted from the stem. Furthermore, above the selected concentration, temperature, and soaking duration level, the fiber damage take place. So, the parameters were selected after the preliminary trials. The retting process was conducted using a water bath.

The complete sample description (Design of experiment) was given in Table 1.

Afterward, the retting process was completed, and the extracted fibers were washed with water and dried in an open atmosphere.

2.3. Chemical composition of the extracted fibers

The analysis of the Chemical composition of the extracted fibers was conducted according to the TAPPI standard test methods [31]. The extracted fibers were dried in an oven at 105 °C for 24 h. The moisture free fibers were ground into a powder form using a Willey ball milling machine. Weighing of the samples was done on a weight balance with 0.01 mg precision. Jute fibers have Cellulose, hemicellulose, and lignin content. The percentages of these components were determined in the chemical composition analysis.

2.3.1. Determination of holocellulose content

Holocellulose consists of cellulose and hemicellulose. The amount of holocellulose in the extracted jute fibers was determined by removing the lignin. For this, 1.25 g of dried powdered fiber samples (W_S), 40 ml of hot distilled water, 0.25 ml of acetic acid, and 0.5 g of sodium chlorite were added to a 250 ml of Erlenmeyer flask. The mixture was heated in a water bath at 70 °C for 6 h. Then after each succeeding hour, 0.25 ml of acetic acid and 0.5 g of sodium chlorite were added to the mixture. The 6 h of chlorinating process

Table 1
DOE (Design of experiments) of the study conducted in this research paper.

Set#	Sample ID	Temperature °C	Time (h)	NaOH Concentration (%)
Set 1	S1 J	60	12	5
	S2 J	60	12	10
	S3 J	60	12	15
	S4 J	60	24	5
	S5 J	60	24	10
	S6 J	60	24	15
	S7 J	60	36	5
	S8 J	60	36	10
	S9 J	60	36	15
Set 2	S10 J	90	12	5
	S11 J	90	12	10
	S12 J	90	12	15
	S13 J	90	24	5
	S14 J	90	24	10
	S15 J	90	24	15
	S16 J	90	36	5
	S17 J	90	36	10
	S18 J	90	36	15
Set 3	S19 J	30	12	5
	S20 J	30	12	10
	S21 J	30	12	15
	S22 J	30	24	5
	S23 J	30	24	10
	S24 J	30	24	15
	S25 J	30	36	5
	S26 J	30	36	10
	S27 J	30	36	15

delignified the fibers from the lignin as shown in Fig. 2.

After that mixture was kept for 24 h in the water bath. After the 24 h reaction period, the mixture was filtered, washed with acetone, and oven dried at 105 °C for 24 h. The weight of the dried sample represents the weight of holocellulose (W_h). The holocellulose content was calculated using Equation (1).

$$Holocellulose\ content\ (H\%) = \frac{W_h}{W_s} \times 100 \tag{1}$$

2.3.2. Determination of lignin content

The lignin in the jute fiber consists of complex aromatic compounds. The main building blocks of lignin are *p* -hydroxyphenyl, guaiacyl, and syringyl.

The lignin content (W_L) in the extracted fibers was determined by calculating the difference between the weight of holocellulose (W_h) and the weight of the sample (W_S).

The percentage of lignin content (L%) was calculated using Equation (2).

$$Lignin\ content\ (L\%) = \frac{W_L}{W_s} \times 100 \tag{2}$$

2.3.3. Determination of α -cellulose content

In a 250 ml glass beaker, the extracted holocellulose was treated with 17.5 % NaOH solution at a temperature of 20 °C. After 5 min, 5 ml of NaOH solution was added to the mixture and allowed to sit for 30 min at 20 °C. Following a 45-min reaction time, distilled water was added to the mixture and after 1 h, the solution was filtered by using the vacuum filtration technique. The sample was washed with distilled water in the vacuum filtration crucible. Then, 10 % acetic acid was poured onto the mixture, suction was applied after 3 min to remove the acetic acid. The sample was then washed with distilled water to remove any remaining acid and neutralized the pH. Subsequently, the sample was oven dried at 105 °C for 24 h. The dry weight of the sample is the weight of α **-cellulose (Wα). The** α **-cellulose** content was calculated according to Equation (3).

$$\alpha - Cellulose\ content\ (AC\%) = \frac{W_\alpha}{W_h} \times 100 \tag{3}$$

2.3.4. Determination of hemicellulose content

The weight of the hemicellulose (W_{hm}) was determined by calculating the difference between the weight of α-cellulose and the weight of the holocellulose.

The Hemicellulose content was calculated according to Equation (4).

$$Hemicellulose\ content\ (HM\%) = \frac{W_{hm}}{W_h} \times 100 \tag{4}$$

2.4. Optical microscopy

The morphological structure of the extracted fibers was analyzed through an optical microscope (Optika Microscope, Itlay).

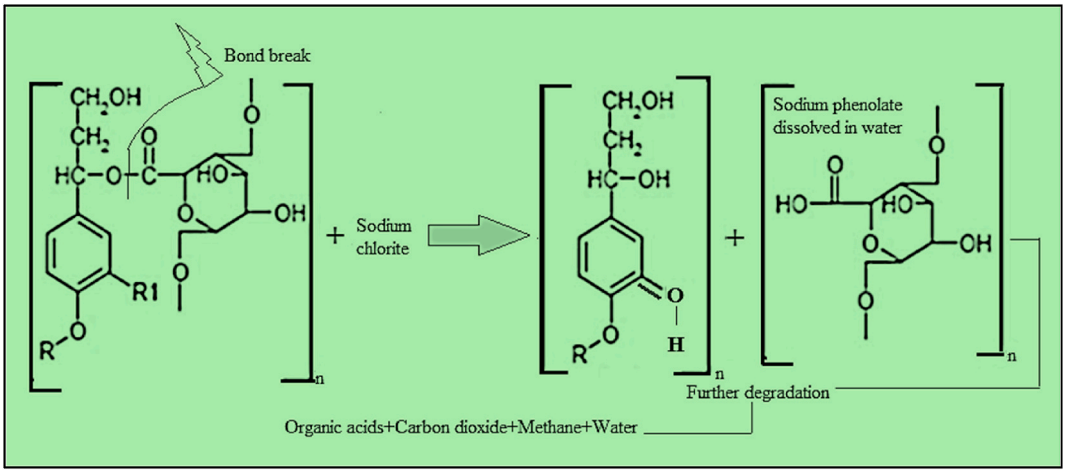

Fig. 2. Delignification process with sodium chlorite.

2.4.1. SEM (scanning electron microscopy)

Morphology was examined through a scanning electron microscope (Quanta 250 EFI) at different magnification levels.

2.5. FTIR (fourier transform infrared spectroscopy)

The functional groups of the extracted jute fibers were characterized through "PerkinElmer FTIR spectrophotometer", in transmittance mode with a wave number ranging from 4000 to 600 cm^{-1}. The sample was placed on the crystal plate and pressure was adjusted between the gripper plate and the crystal plate to ensure consistent contact between the crystal plate and the sample.

2.6. XRD (X-ray diffraction)

The crystallographic information of the extracted fibers was analyzed through an X-ray diffractometer, XPret Pro (PANalytical). The observations were collected from 10° to 40° at 2θ with a step size of 0.05°. Crystallinity index (CI) was measured as the ratio between the area of all the crystalline peaks (A_c) to the area of all the crystalline and amorphous peaks (A_{Total}) according to Equation (5).

$$Crystallinity\ Index(CI\%) = \frac{A_C}{A_{Total}} \times 100 \tag{5}$$

2.7. Fiber linear density and single fiber strength

The linear density was calculated according to ASTM D 1577. The tensile strength (Tenacity cN/tex) and elongation (%) properties of the extracted fibers were measured using a single fiber tensile strength tester (M250-2.5CT Testometric, Rochdale, England). The test was conducted following ASTM D 3822 guidelines, with the machine operated at a 25 mm gauge length and a 50 N load applied to the samples at an extension rate of 100 mm/min.

3. Grey relational analysis (GRA)

The GRA utilized experimental data related to quality criteria to create grey relations. The findings were used to create grey relational grades and rate each data series. The GRA involves five steps to evaluate the quality characteristics of the experimental data [32,33].

•**Step-1:** Calculate the S/N ratio of the responses to measure the deviation of the data from the desired value. The S/N ratio is calculated based on the quality characteristics: either the higher value is better, the lower is better, or the nominal is better. In this study, the fiber linear density, lignin content %, and hemicellulose content% have "lower is better" characteristics, while fiber tenacity, elongation, holocellulose%, and Alpha cellulose % have "higher is better" characteristics. The S/N ratio (higher is better HB) and (lower is better LB) are calculated according to Equations (6) and (7), respectively.

$$\frac{S}{N} ratio\ (HB) = -10\ log\left(\frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{km}^2}\right) \tag{6}$$

$$\frac{S}{N} ratio\ (LB) = -10\ log\left(\frac{1}{n}\sum_{k=1}^{n}y_{km}^2\right) \tag{7}$$

in the above equations: n = number of experiments and Y_{km} is the kth replicate of the mth response.

- **Step-2:** The Y_{km} values were normalized as Z_{km} ($0 \leq Z_{km} \leq 1$) to reduce data variability. The data were normalized according to Equations (8) and (9) for the responses (higher is better HB) and (lower is better LB) respectively.

$$Z_{km}(HB) = \frac{Y_{km} - min(Y_{km})}{max(Y_{km}) - min\ (Y_{km})} \tag{8}$$

$$Z_{km}\ (LB) = \frac{max\ (Y_{km}\ ) - Y_{km})}{max(\ Y_{km}\ ) - min(Y_{km})} \tag{9}$$

- **Step 3:** Calculated the quality loss function (**Δ**) according to Equation (10).

$$\Delta = |Y_0 - Y_{km}| \tag{10}$$

- **Step-4**: Calculated the grey relational coefficient (GC) for the normalized values according to Equation (11).

$$GC_{km} = \frac{\Delta_{min} + \delta\Delta_{max}}{\Delta_{km} + \delta\Delta_{max}} \tag{11}$$

- **Step-5**: Calculated the grey relation grade (G_k) according to Equation (12).

$$G_k = \frac{1}{m}\sum GC_{km} \tag{12}$$

4. Results and discussion

4.1. Chemical composition analysis

The surface plots of holocellulose content %, lignin content %, alpha-cellulose content %, and hemicellulose content % are shown in Fig. 3(a–d) respectively. The results indicate that as the temperature increased from 30° to 90 °C, the time from 12 h to 36 h, and the NaOH concentration from 5 % to 15 %, the lignin content decreased from 22.20 % to 11.12 % and hemicellulose content decreased from 22.75 % to 21.75 %. Meanwhile, the content of holocellulose and alpha-cellulose increased from 77.8 % to 88.88 %, and 59.66 %–79.55 % respectively. The chemical retting of the jute stems with different concentrations of NaOH, times, and temperature not only increased the cellulose content in the extracted fibers but also decreased the lignin content. The retting treatment provided spinnable jute fibers, which require no further softening treatment after the retting process. The extracted fibers have the high amount of alpha

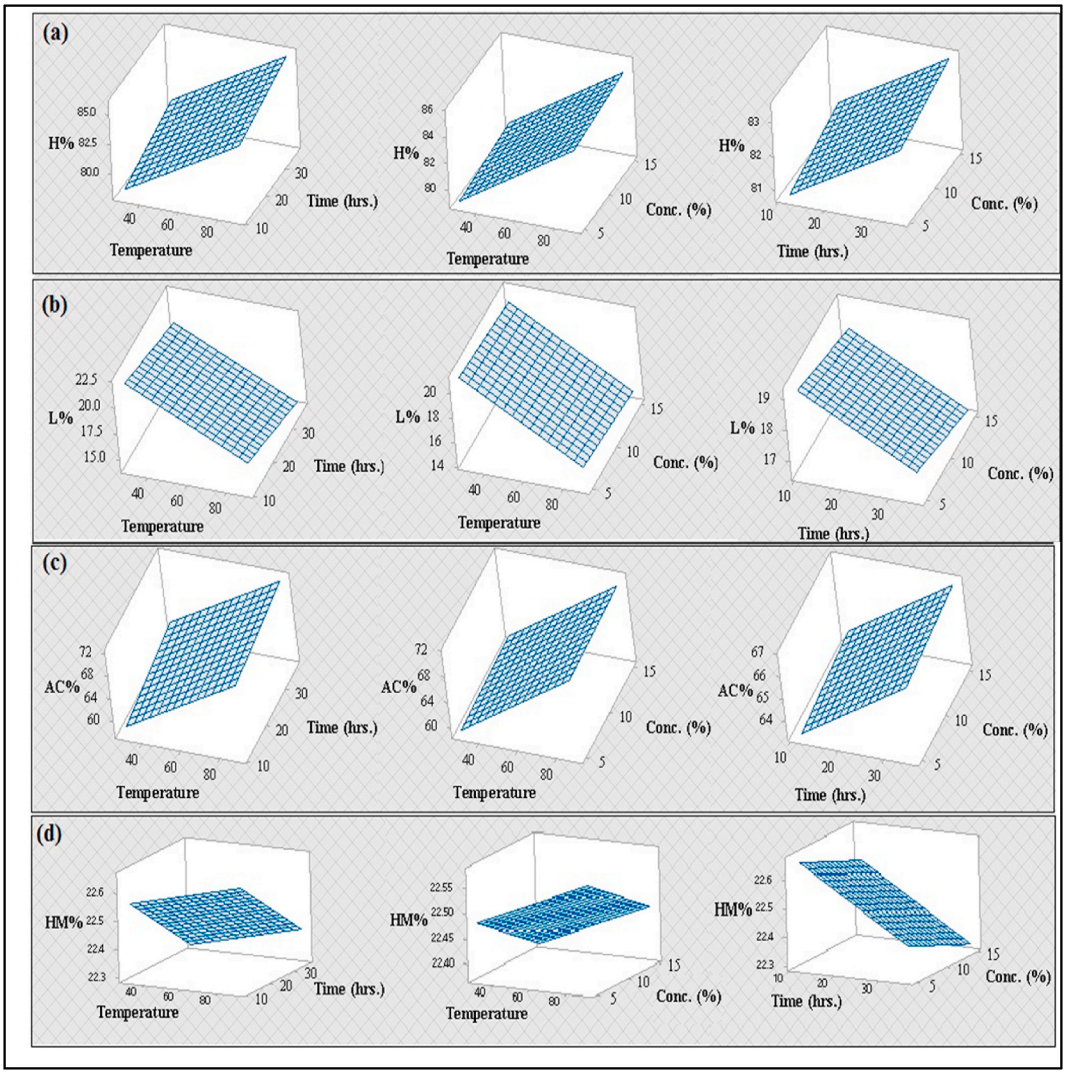

Fig. 3. Surface plots of (a) Holocellulose content % (b) Lignin content % (c) Alpha cellulose content % (d) Hemicellulose content %.

cellulose content and very less amount of lignin. The removal of lignin from the fiber surface provides the softening, bending and flexibility characteristics which make them spinnable for use in apparel applications.

4.2. SEM and optical microscopy

Microscopic images of jute stem and chemically retted jute fibers are shown in Fig. 4. Fibers are bounded with the lignin, gummy material, and waxes in the stem structure as shown in Fig. 4(a). After the chemical retting process the lignin-free smooth jute fibers are depicted in Fig. 4(b–f).

The jute fibers had a smooth, cylindrical, and lustrous external surface. The structure of jute fibers is multicellular with irregular cell wall thickness as shown in SEM images in Fig. 5(a and b) [34].

4.3. FTIR spectrum (fourier transform infrared spectroscopy)

FTIR spectrum of the jute stem and extracted fibers is shown in Fig. 5. The sharp peaks occurring in the region of 3300 cm^{-1}-2700 cm^{-1} were due to the stretching vibration of the C–H group, which is present in cellulose and hemicellulose structures [35]. As shown in Fig. 6, the peak intensity of the C–H group increased with the increase in the retting time (12–36 h), temperature (30–90 °C), and NaOH concentration (5–15 %).

The peaks in the region of 3650 cm^{-1}-3200 cm^{-1} were due to the stretching vibration of the O–H group present in the structure of the cellulose, hemicellulose, and lignin [36,37]. The O–H groups in the jute fiber structure were responsible for intermolecular and intramolecular hydrogen bonding. The peaks in the region of 1050 cm-1 to 1000 cm-1 were due to the stretching of the C–O functional group [38]. The peak at 1742 cm^{-1} in the S18 J sample attributed to the C═O functional group present in the hemicellulose [6,36].

4.4. XRD (X-ray diffraction) spectrum

The X-ray diffraction spectrum of jute stem and chemically retted extracted fibers is shown in Fig. 7. The diffraction peaks ($2\theta =$ 22.29°. 22.59°, 22.69°,22.84°, 23.10°,23.50°) are sharp and narrow, indicating that these peaks belong to the crystalline regions of the cellulose, specifically the (002) crystal face. Additionally, the diffraction peaks at around $2\theta = 13.0°–18.0°$ represent the crystal face of cellulose [37].

The intensity of the diffraction peaks shows that the crystallinity of the fibers increased with the longer retting time, higher

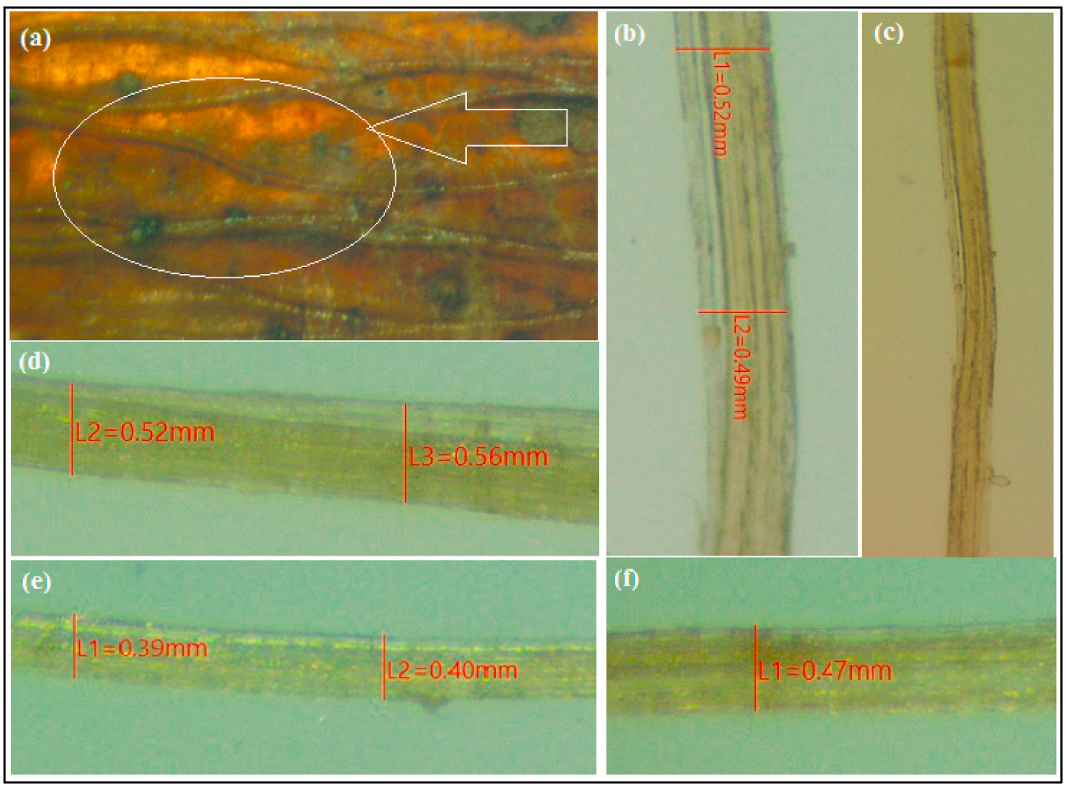

Fig. 4. Microscopic images of (a) Jute stem (b–f) extracted jute fibers.

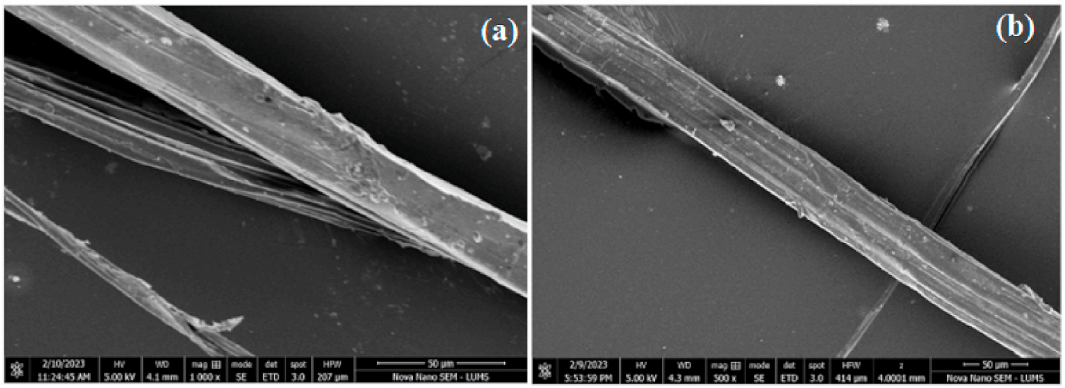

Fig. 5. SEM images of (a) raw jute (b) extracted jute fibers.

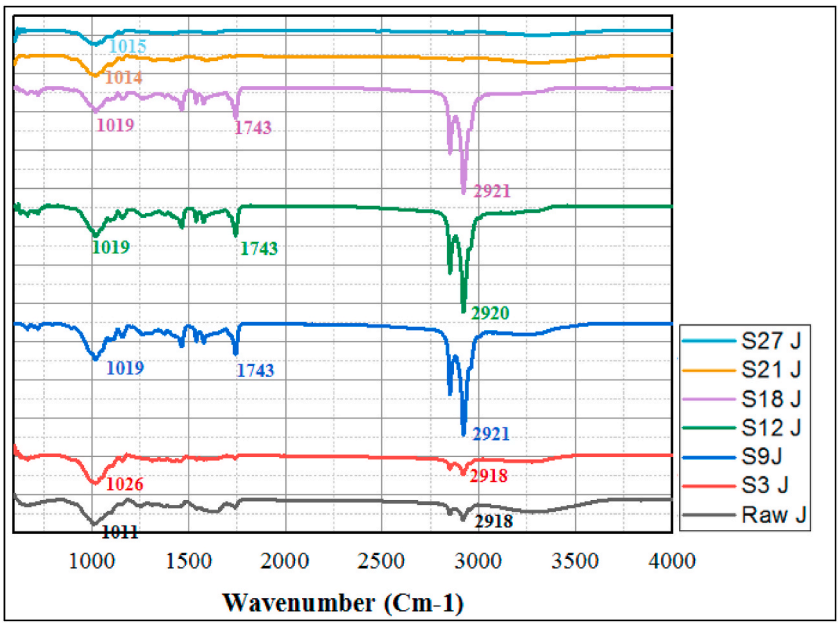

Fig. 6. FTIR spectrum of jute stem and chemically retted extracted jute fibers.

temperature, and higher concentration of NaOH. The S18 J sample showed the highest crystallinity. This increase in crystallinity results in an increase in cellulose content % and a decrease in lignin content % in the extracted jute fibers. Previous studies have revealed that, during alkali treatment, the hydroxide ions may not fully penetrate the crystal structure of the cellulose at low NaOH concentration resulting in a partially crystalline structure. However, at higher NaOH concentrations, the hydroxide ions can fully penetrate the cellulose crystal structure leading to an increase in the crystallinity of the fibers [39]. Crystallinity index calculated from the XRD spectrum is given below in Table 2.

The crystallinity index (CI)% was increased from 62.4 % to 70.12 % after the retting treatment. The increased in the crystallinity index is associated with the removal of lignin and increased of cellulose content in the extracted fibers. The higher crystallinity index associated with the higher tensile strength of the microfibrils.

4.5. Fiber linear density and single fiber strength analysis

The linear density, tensile strength, and elongation of the fiber have a direct relationship with the fiber spinnability characteristics [40]. The surface plots of the fiber linear density (Tex), Fiber elongation (%), and fiber tenacity (cN/tex) are illustrated in Fig. 8(a–c) respectively.

The results indicate that with the increase in temperature from 30° to 90 °C, Time from 12 h to 36 h, and NaOH concentration from 5 % to 15 %, the tensile strength increased from 18.03 cN/Tex to 53.02 cN/Tex. The hydroxyl groups in the cellulose unit cells, when interacting with the NaOH, caused the swelling of the cellulose chains resulting in chain alignment. The alignment of the chains with

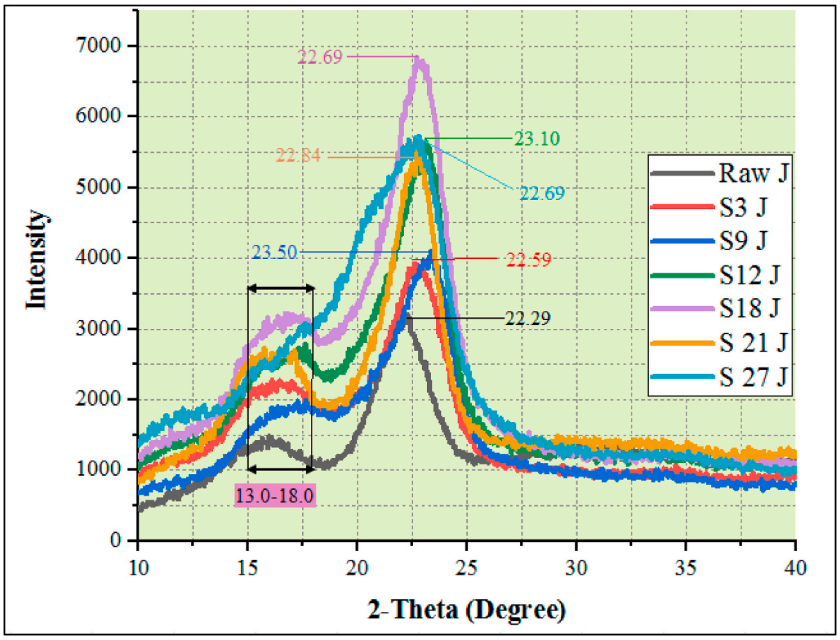

Fig. 7. XRD spectrum of jute stem and extracted jute fibers.

Table 2
Crystallinity index (CI)% of jute stem and extracted jute fibers.

Sample ID	Crystallinity Index (CI)%
Raw J	62.4
S3 J	64.8
S9 J	65.2
S12 J	69.72
S18 J	70.12
S21 J	59.9
S27 J	60.22

the fiber axis increased the tensile strength of the fibers [39].

Meanwhile, the linear density of extracted fibers decreased from 9.05 Tex to 2.18 Tex. The results indicate that the linear density of the extracted fibers was comparable to the alkali-treated fibers which are treated after the retting process [41].

4.6. Grey relational analysis results

The Grey relational analysis for the responses was performed according to the procedure mentioned in Section 3.

The values of the S/N ratio of all the responses are shown in Table 3.

The values of the normalized S/N ratio of all the responses are shown in Table 4.

The values of the quality loss function of all the responses are shown in Table 5.

The values of the grey relation coefficient and grey grades of all the responses are shown in Table 6.

The multiple responses are evaluated based on the grey relational grade. This approach allows for the optimization of just one grey relational grade instead of dealing with numerous process responses. The grey relational order is determined by placing the series according to their grey relational grades. Generally, the larger the grey relational grade, the better the numerous performance features. A higher grey relational grade indicates that the S/N ratio is closer to the normalized S/N ratio, implying a more ideal characteristic set-up [42,43].

Therefore, the sample S 15J in Table 5 has the highest grey relational grade indicating the optimal performance parameters to achieve the maximum values of all the characteristics in spinnable jute fibers.

5. Conclusion

In this research, a simple and novel retting technique for jute steams is proposed. FTIR and XRD results showed that at higher temperatures, the NaOH treatment reduced the lignin content and increased the crystallinity of the extracted jute fibers. The Lignin

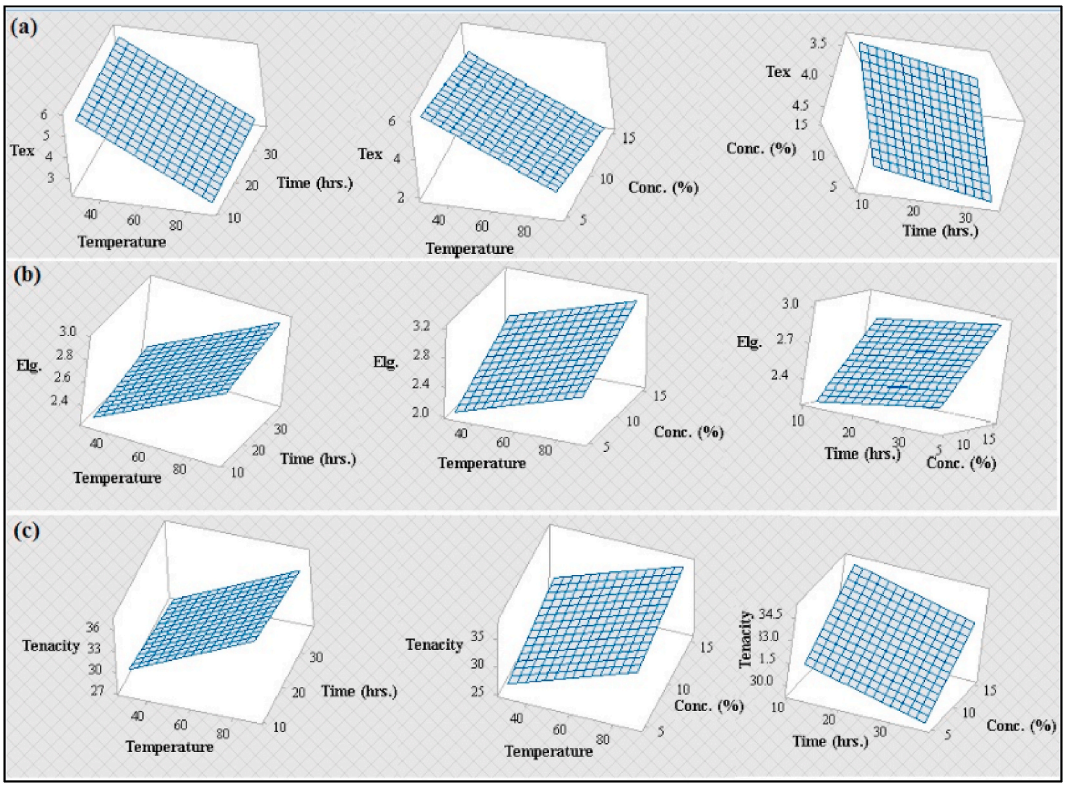

Fig. 8. Surface plots of (a) fiber linear density Tex (b) fiber elongation % (c) fiber tenacity cN/Tex.

Table 3
The values of S/N ratios for all the responses.

Sample ID	H%	L%	AC%	HM%	Tex	Elongation	Tenacity
S1 J	38.3	−25	35.8	−27.01	−13	7.31	32.52
S2 J	38.3	−25	35.8	−27.02	−9.1	7.99	32.13
S3 J	38.3	−25	35.8	−27.04	−11	11.08	32.00
S4 J	38.3	−25	36.3	−27.05	−11	11.17	27.01
S5 J	38.3	−25	36.3	−27.06	−7.5	11.00	31.81
S6 J	38.4	−25	36.3	−27.07	−9.6	10.68	30.97
S7 J	38.4	−25	36.6	−27.08	−10	6.26	28.01
S8 J	38.4	−25	36.6	−27.09	−8.7	10.08	29.36
S9 J	38.4	−25	36.7	−27.10	−8.6	10.50	30.21
S10 J	38.4	−25	36.8	−27.10	−11	12.07	28.17
S11 J	38.4	−24	36.8	−27.10	−11	3.39	25.74
S12 J	38.4	−24	36.9	−27.12	−8	7.35	30.48
S13 J	38.4	−24	37	−27.12	−7.2	3.43	32.31
S14 J	38.4	−24	37	−27.13	−8.6	8.50	30.49
S15 J	38.4	−24	37	−27.14	−6.8	13.14	34.49
S16 J	38.5	−24	37	−27.06	−12	8.68	28.72
S17 J	38.7	−23	37.1	−26.95	−11	7.15	32.16
S18 J	39	−21	37.1	−26.67	−10	7.30	32.53
S20 J	37.8	−27	35.5	−27.07	−12	4.65	32.34
S21 J	37.8	−27	35.5	−27.08	−14	5.70	27.24
S22 J	37.9	−27	35.5	−27.03	−19	4.25	30.25
S23 J	37.9	−26	35.4	−27.01	−16	9.66	25.12
S24 J	38	−26	35.4	−27.00	−13	2.66	28.46
S25 J	38	−26	35.5	−26.95	−17	3.32	29.26
S26 J	38.1	−26	35.5	−26.92	−15	6.08	29.24
S27 J	38.1	−26	35.6	−26.92	−17	11.85	26.20

Table 4
The values of the normalized S/N ratio of all the responses.

Sample ID	H%	L%	AC%	HM%	Tex	Elongation	Tenacity
S1 J	0.44	0.66	0.20	0.713	0.52	0.44	0.78949
S2 J	0.44	0.66	0.21	0.744	0.19	0.51	0.74775
S3 J	0.44	0.65	0.23	0.774	0.35	0.80	0.73387
S4 J	0.45	0.65	0.51	0.805	0.33	0.81	0.20199
S5 J	0.45	0.64	0.51	0.831	0.06	0.80	0.71457
S6 J	0.47	0.63	0.52	0.839	0.23	0.77	0.62392
S7 J	0.47	0.63	0.7	0.870	0.27	0.34	0.30819
S8 J	0.48	0.62	0.7	0.878	0.16	0.71	0.453
S9 J	0.49	0.61	0.75	0.899	0.15	0.75	0.54371
S10 J	0.5	0.6	0.83	0.916	0.36	0.90	0.32572
S11 J	0.51	0.59	0.84	0.915	0.3	0.07	0.06598
S12 J	0.52	0.58	0.91	0.941	0.1	0.45	0.57241
S13 J	0.53	0.57	0.92	0.958	0.03	0.07	0.76706
S14 J	0.54	0.56	0.92	0.971	0.15	0.56	0.57352
S15 J	0.54	0.56	0.94	1.000	0	1.00	1
S16 J	0.63	0.47	0.97	0.825	0.38	0.57	0.38393
S17 J	0.74	0.35	1.00	0.596	0.3	0.43	0.75164
S18 J	1	0	1	0.000	0.28	0.44	0.79098
S20 J	0	1	0.06	0.841	0.38	0.19	0.7702
S21 J	0.01	1	0.06	0.868	0.62	0.29	0.22611
S22 J	0.06	0.96	0.05	0.769	1	0.15	0.54796
S23 J	0.11	0.93	0	0.708	0.78	0.67	0
S24 J	0.13	0.91	0.01	0.694	0.53	0.00	0.35598
S25 J	0.18	0.87	0.07	0.597	0.82	0.06	0.44157
S26 J	0.23	0.83	0.07	0.523	0.64	0.33	0.43965
S27 J	0.25	0.82	0.09	0.533	0.81	0.88	0.1154

Table 5
The values of quality loss function values of all the responses.

Sample ID	H%	L%	AC%	HM%	Tex	Elongation	Tenacity
S1 J	0.563	0.34	0.8	0.29	0.48	0.56	0.21
S2 J	0.559	0.34	0.79	0.26	0.81	0.49	0.25
S3 J	0.556	0.35	0.77	0.23	0.65	0.20	0.27
S4 J	0.552	0.35	0.49	0.20	0.67	0.19	0.80
S5 J	0.547	0.36	0.49	0.17	0.94	0.20	0.29
S6 J	0.534	0.37	0.48	0.16	0.77	0.23	0.38
S7 J	0.53	0.37	0.3	0.13	0.73	0.66	0.69
S8 J	0.518	0.38	0.3	0.12	0.84	0.29	0.55
S9 J	0.51	0.39	0.25	0.10	0.85	0.25	0.46
S10 J	0.501	0.4	0.17	0.08	0.64	0.10	0.67
S11 J	0.485	0.41	0.16	0.08	0.7	0.93	0.93
S12 J	0.48	0.42	0.09	0.06	0.9	0.55	0.43
S13 J	0.471	0.43	0.08	0.04	0.97	0.93	0.23
S14 J	0.46	0.44	0.08	0.03	0.85	0.44	0.43
S15 J	0.456	0.44	0.06	0.00	1	0.00	0.00
S16 J	0.369	0.53	0.03	0.18	0.62	0.43	0.62
S17 J	0.26	0.65	0	0.40	0.7	0.57	0.25
S18 J	0	1	0	1.00	0.72	0.56	0.21
S20 J	1	0	0.94	0.16	0.62	0.81	0.23
S21 J	0.994	0	0.94	0.13	0.38	0.71	0.77
S22 J	0.937	0.04	0.95	0.23	0	0.85	0.45
S23 J	0.895	0.07	1	0.29	0.22	0.33	1.00
S24 J	0.872	0.09	0.99	0.31	0.47	1.00	0.64
S25 J	0.815	0.13	0.93	0.40	0.18	0.94	0.56
S26 J	0.768	0.17	0.93	0.48	0.36	0.67	0.56
S27 J	0.755	0.18	0.91	0.47	0.19	0.12	0.88

content decreased by 49.9 % and the alpha-cellulose content increased by 33.33 %.

The mechanical properties of the fibers were also improved in terms of fiber linear density, tensile strength (Tenacity cN/Tex), and elongation (%). The NaOH treatment removed lignin, resulting in finer and strongest fibers. The maximum fine fibers achieved in this research had a linear density of 2.18 Tex, with a tenacity of 53.02 cN/tex and an elongation of 4.54 %.

Grey relational analysis (GRA) revealed that the highest values of all the fiber properties were achieved at the process parameters of (NaOH = 15 %, Temperature = 90 °C, and Time = 24 h). The extracted spinnable jute fibers are suitable for ring spinning to produce yarn without any further chemical treatment.

Table 6
The values of grey relation coefficients and grey grades of all the responses.

Sample ID	H%	L%	AC%	HM%	Tex	Elongation	Tenacity	G_k	Grey relational order
S1 J	0.64	0.75	0.56	0.78	0.68	0.64	0.83	0.69	**18**
S2 J	0.64	0.74	0.56	0.80	0.55	0.67	0.80	0.68	**19**
S3 J	0.64	0.74	0.56	0.82	0.61	0.84	0.79	0.71	**14**
S4 J	0.64	0.74	0.67	0.84	0.60	0.84	0.56	0.70	**15**
S5 J	0.65	0.74	0.67	0.86	0.51	0.83	0.78	0.72	**10**
S6 J	0.65	0.73	0.67	0.86	0.56	0.81	0.73	0.72	**13**
S7 J	0.65	0.73	0.77	0.88	0.58	0.60	0.59	0.69	**20**
S8 J	0.66	0.72	0.77	0.89	0.54	0.77	0.65	0.71	**12**
S9 J	0.66	0.72	0.80	0.91	0.54	0.80	0.69	0.73	**8**
S10 J	0.67	0.72	0.85	0.92	0.61	0.91	0.60	0.75	**2**
S11 J	0.67	0.71	0.86	0.92	0.59	0.52	0.52	0.68	**22**
S12 J	0.68	0.70	0.92	0.94	0.53	0.64	0.70	0.73	**9**
S13 J	0.68	0.70	0.92	0.96	0.51	0.52	0.81	0.73	**7**
S14 J	0.68	0.70	0.93	0.97	0.54	0.69	0.70	0.74	**4**
S15 J	0.69	0.69	0.94	1.00	0.50	1.00	1.00	0.83	**1**
S16 J	0.73	0.65	0.97	0.85	0.62	0.70	0.62	0.73	**5**
S17 J	0.79	0.61	1.00	0.71	0.59	0.64	0.80	0.73	**6**
S18 J	1.00	0.50	1.00	0.50	0.58	0.64	0.83	0.72	**11**
S20 J	0.50	1.00	0.51	0.86	0.62	0.55	0.81	0.69	**3**
S21 J	0.50	1.00	0.52	0.88	0.72	0.58	0.56	0.68	**16**
S22 J	0.52	0.96	0.51	0.81	1.00	0.54	0.69	0.72	**17**
S23 J	0.53	0.93	0.50	0.77	0.82	0.75	0.50	0.69	**21**
S24 J	0.53	0.92	0.50	0.77	0.68	0.50	0.61	0.64	**24**
S25 J	0.55	0.88	0.52	0.71	0.84	0.52	0.64	0.67	**25**
S26 J	0.57	0.86	0.52	0.68	0.74	0.60	0.64	0.66	**26**
S27 J	0.57	0.85	0.52	0.68	0.84	0.89	0.53	0.70	**23**

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The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

Code availability

Not applicable.

Ethics approval

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Consent to participate

Not applicable.

Consent for publication

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Bushra Mushtaq: Data curation, Validation, Writing – original draft. **Faheem Ahmad:** Conceptualization, Validation, Visualization. **Yasir Nawab:** Formal analysis, Funding acquisition, Resources, Supervision, Writing – review & editing. **Sheraz Ahmad:** Funding acquisition, Project administration, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

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

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