

Preparation of regenerated cellulose from rice straw lignocellulosic waste and its use for reinforced paper products

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ABSTRACT: Rice straw waste is a lignocellulosic waste produced by farmers in large quantities. In this study, regenerated cellulose (RC) from rice straw was prepared by dissolving rice straw holocellulose (HC) in NaOH/Urea/Thio-urea/Water solution by the freeze-thawing process. The crystallinity index of RC was calculated at 31%, which is out of the crystallinity range of 39%–69% that has been previously suggested.

The study indicated that the RC is amorphous with a low degree of polymerization (638) and higher hydroxyl group content as compared to HC. The fiber length of RC was found to be 26.7% shorter; however, the width of RC was 21.2% higher as compared to HC. Reduced kinked fiber content was observed in the fraction of RC (18.3%) as compared with HC (39.1%), and a higher curl index of fiber was observed more so in HC (10.5%) than RC (5.6%). Because of the regeneration process, the fiber length was reduced and a fines element content of about 96% was observed in RC compared to the initial fines content of HC (56.9%). Irrespective of the high fines element content of RC, the composite paper of rice straw bleached pulp and RC fibers was developed with an increase in the tensile index from 41.4 N.m/g to 71.2 N.m/g and an increase in the burst index from 4.7 kPa.m²/g to 5.3 kPa.m²/g with the addition of 5% and 15% RC, respectively. However, enhanced tear index of paper was observed up to 5% and then it declined upon further addition of RC. The study revealed that regenerated cellulose can be used as a strength additive to overcome the shortcomings of low mechanical properties in paper products.

Application: Regenerated cellulose produced in this study has an amorphous structure with very high content of hydroxyl groups in its chain, which can improve the physical properties of paper. Reinforced composite paper from rice straw pulp was produced and developed using this RC, and significant improvement in the tensile strength properties was found.

Rice is one of the world's largest crops and its production worldwide for the year 2020-2021 is projected at 682.3 million metric tons [1]. In India, rice straw alone is produced in large quantities, contributes to about 23% of the total agricultural crop residue [2], and contains a huge amount of paddy by its weight [3,4]. Rice straw is a low-value agricultural residue, and it is expected that rice straw may be an alternative to wood as a source of cellulose-based substances [5]. India is suffering from the acute problem of rice straw burning that causes atmospheric pollution, health issues, and reduction in soil fertility by killing useful insects and beneficial microbes, etc. Therefore, to avoid the effects of burning, utilization of rice straw for various activities is being promoted, such as for making paper and paperboard, for ethanol and biogas production [6-9], and for regenerated cellulose (RC) production [10]. By adopting these practices for the utilization of rice straw, burning can be avoided. The RC and its composite have been explored in many fields, such as separation techniques, biomedical applications, wastewater treatment, papermaking, and the textile industry.

Cellulose molecules are a crystalline linear polymer of D-anhydroglucopyranose unit that cannot be melted in a

common solvent or aqueous solution due to inter- and intra-molecular hydrogen bonding [11]. Several studies have been carried out for making regenerated cellulose by dissolving cellulose in more effective solvents such as N-methyl morpholine-N-oxide (MMNO/H₂O), trifluoroacetic acid (TFA)/1,2-dichloromethane, and LiCl/dimethylacetamide (DMAc) solutions. Among these, the (MMNO/H₂O) solution was considered the most appropriate solvent for the dissolution of cellulose [12], but it has some drawbacks, such as the requirement of high temperature, the formation of byproducts, and a high operating cost. The oldest viscose process with sodium hydroxide/carbon disulfide (NaOH/CS₂) for the preparation of regenerated cellulose fibers is predominately being used. This oldest process also has some disadvantages, such as the evolution of toxic gases like hydrogen sulfide (H₂S) and CS₂ [13]. Several authors have suggested the dissolution of cellulose in alkaline solution (NaOH/water) at low temperature, preferably below freezing point [14-20], and observed the solubility of cellulose increased by the addition of urea/thio-urea as an additive to the alkaline solution [21-23]. These solutions are stable at low to high temperatures, and the solubility of cellulose depends on the percentage of addi-

tive in the alkaline solution and its degree of polymerization (DP) [18,24]. Recently, different grades of pulp — such as dissolving, bleached hardwood, and tissue grades — were used for RC production in a green aqueous solution of NaOH/urea/thiourea by a freeze-thawing process [25].

This research work aimed to establish commercial utilization of low-cost rice straw for the production of RC in a green solvent (NaOH/urea/thiourea). Based on the literature, no work is reported on the production of RC from rice straw using green solvents and its utilization as strength additives to improve the mechanical properties of paper products. Agro-based paper industries are facing a series of problems related to strength development in paper products. Thus, this work was created in an effort to explore the application of RC as a strength additive in papermaking. Therefore, the development of RC from rice straw will be helpful in minimizing environmental load in terms of pollution due to the burning of straw, as well as for improving the quality of products for paper and packaging industries.

MATERIALS AND METHODS

Rice straw was collected from farmers of western Uttar Pradesh in India and chopped to about 2–3 cm in length. Pure urea and thiourea were obtained from Sigma-Aldrich (St. Louis, MO, USA), and NaOH of an analytical grade was obtained from Fisher Scientific (Waltham, MA, USA). Chemical constituents of rice straw were determined by laboratory procedures as per the TAPPI Standard Test Methods given in **Table I**.

Preparation of holocelluloses

Chopped rice straw was used to generate pulp using a soda process in a rotary digester with 14% active alkali as NaOH, and cooking was done at 165°C for about 30 min. After cooking, the pulp was thoroughly washed with hot and cold water to remove black liquor from the pulps. About 10 g of oven-dried pulps were dispersed in 300 mL of distilled water, heated to 80°C in a water bath, and then 8 g of so-

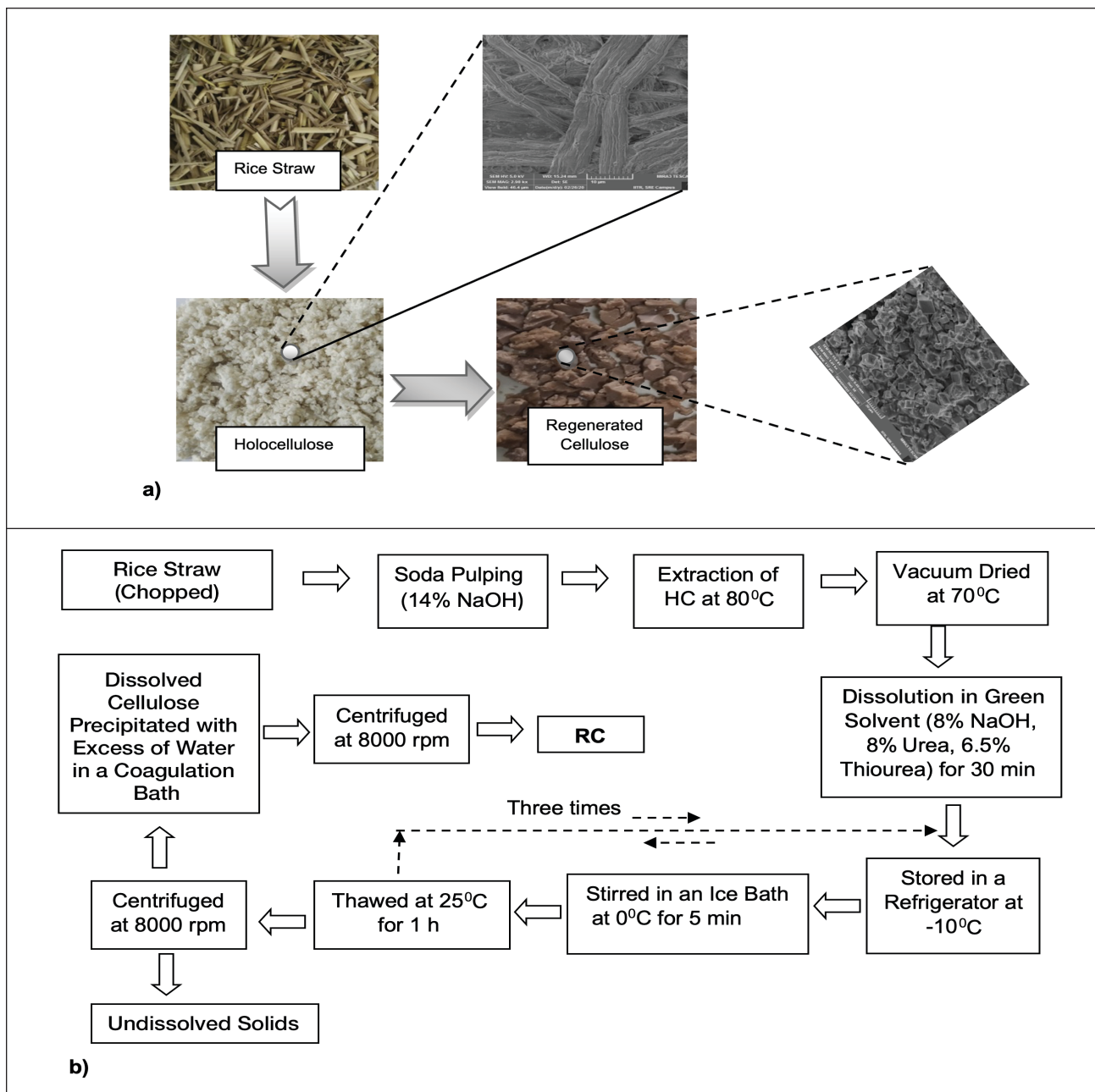
dium chlorite was added; to maintain the pH between 3–3.5, 3.0 mL of acetic acid was also added to the pulp suspension. This step was repeated every hour for around three to four times, and then washed pulp with minimum lignin content was considered as HC [11].

Preparation of regenerated cellulose

For the preparation of RC, 10 g of oven-dried HC was dispersed in 200 g of NaOH/urea/thiourea/water solution [27] for about 30 min with a Remi mechanical stirrer to homogenise the pulp and solvent [28]. The pulp suspension was then stored in a refrigerator at about -10°C for around 12 h. After that, the sample was stirred vigorously while keeping the sample in an ice bath for about 5 min and then thawed in a water bath maintained at 25°C for 1 h, with stirring at a time interval. The same process was repeated three times to achieve maximum dissolution of pulp in the solvent. The sample was then centrifuged at about 8000 rpm for 5 min to separate the dissolved cellulose [29]. Next, the dissolved cellulose was precipitated in a water bath having an excess of distilled water to produce RC. A graphical abstract and flow diagram of the entire process for preparing RC from rice straw are shown in **Figs. 1a-1b**. For the dissolution of 10 g of the sample, about 120–130 mL of solvents containing dissolved cellulose were generated, which required about 500 mL of distilled water for the re-precipitation of cellulose. It was expected that for 1 metric ton of RC preparation, approximately 119 m³ of effluent would be generated. There was a problem with the recycling of effluents generated, and there is a need for future research on recyclability. The kinetics of regeneration of cellulose mainly occur due to the relative velocities of coagulant and solvent by a counter-diffusion process, meaning diffusion of the solvent into the coagulation bath and coagulants from the bath into the solution [30]. During the pouring of solvents into the coagulant, exchange of solvent molecules with non-solvent compounds occurs and leads to the desolvation of cellulose molecules and the reformation of intra- and inter-

Test Parameters	Standard Test Method
Solvent extractive	TAPPI T 204 cm-97 "Solvent extractives of wood and pulp"
1% NaOH solubility	TAPPI T 212 om-02 "One percent sodium hydroxide solubility of wood and pulp"
Hemicellulose	TAPPI T 203 cm-99 "Alpha, beta and gamma-cellulose in pulp"
Cellulose	TAPPI T 203 cm-99 "Alpha, beta and gamma-cellulose in pulp"
Holocellulose	Wise, E., Murphy, M., and D'Addieco, A.A [26].
Lignin	TAPPI T 222 om-06 "Acid-insoluble lignin in wood and pulp"
Ash	TAPPI T 211 om-12 "Ash in wood, pulp, paper and paperboard: combustion at 525°C"
Silica	TAPPI T 245 cm-07 "Silicate and silica in pulp (wet ash method)"

I. Standard followed during the analysis of chemical constituents of rice straw (NaOH = sodium hydroxide).



1. a) Graphical abstract and b) flow diagram of the preparation of regenerated cellulose (RC) from rice straw (NaOH = sodium hydroxide).

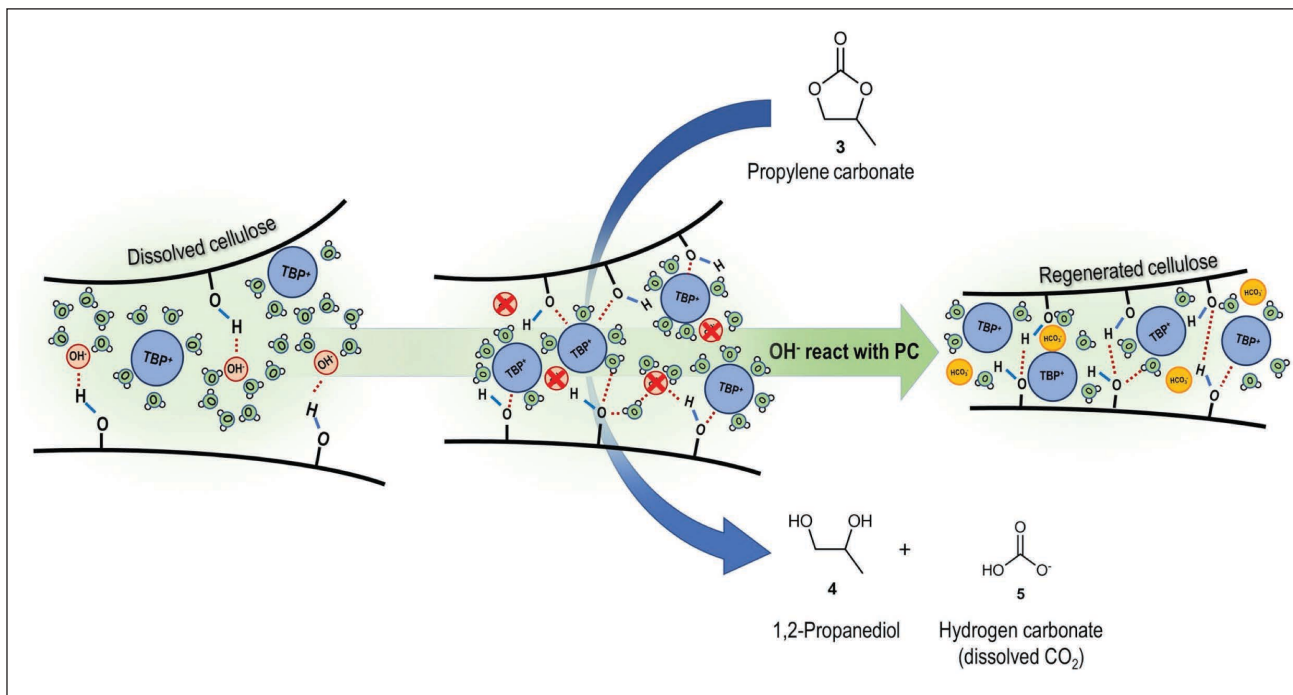
molecular hydrogen bonding [28]. A mechanism of cellulose dissolution by tetra-butyl phosphonium hydroxide (TBPH) and precipitation by propylene is proposed for dissolution and precipitation of cellulose, as shown in **Fig. 2**. Hydroxide ions (-OH) of TBPH can break down the hydrogen bonds between cellulose chains, leading to cellulose depletion; similar mechanisms occur in the case of green solvent where the hydroxyl groups of NaOH break down the hydrogen bonds between cellulose chains. For re-precipitation of cellulose chains, propylene carbonate (PC) was added into dissolved cellulose; the nucleophilic attacks of -OH ions of TBPH occurred with PC and produced 1,2 pro-

panediol and hydrogen carbonate. Thus, no hydroxide ions are available to stabilize the cellulose in a dissolved state, and hydrogen bonds are re-established between cellulose chains [31].

CHARACTERIZATIONS

Fiber analysis

The pulp and RC samples were disintegrated and diluted to make a 50-ppm solution for the characterization of fiber using a MorFi Neo fiber analyzer (Techpap; Gières, France). This analyzer has a camera for image and analysis of fiber characteristics such as length, width, kink, curl, coarseness, etc. The



2. Proposed cellulose dissolution and precipitation method caused by propylene carbonate [31].

diluted samples were also used to make a microscopic slide for viewing the images of cellulose fibers in an electron microscope (Model-Olympus BX51, Olympus; Tokyo, Japan) as per the method ISO 9184-1:1990 “Paper, board and pulps — Fibre furnish analysis — Part 1: General method.”

Viscosity and DP

The viscosity of pulp indicates the average degree of polymerization (DP) of cellulose. Viscosity was measured by measuring the reflux time of cellulose solution dissolved in 0.5 M cupirethylenediamine (CED) solution in a capillary viscometer tube at $25 \pm 1^\circ\text{C}$, as per TAPPI Standard Test Method T-230 om-08 “Viscosity of pulp (capillary viscometer method).” The viscosity of cellulose was calculated using Eq. 1, and the intrinsic viscosity was obtained from the viscosity conversion table as per TAPPI T 206 m-55 “Cuprammonium disperse viscosity of pulp.” The DP was calculated by using Eq. 2 [32]:

$$V = C \times t \times d \quad (1)$$

$$\text{DP}^{0.85} = 1.1 \times \eta \quad (2)$$

where:

V = viscosity of cupirethylenediamine solution at 25°C , mpa.s (cP)

C = viscosity constant of capillary tube found by calibration

t = average reflux time, s

d = density of pulp solution, g/cm^3 (1.052)

η = intrinsic viscosity

XRD analysis

The crystallinity index (CI) of samples was performed by X-ray diffraction (XRD) analysis. This technique is used for the determination of the atomic and molecular structure of a material by measuring the intensity of incident and scattered X-ray at an angle throughout the material. The CI was calculated by fractionating the difference between the minimum intensity of the peak 101 amorphous bands (I_{am}) and maximum intensity peak that represents the crystalline portion (I_c) of peak 002 to the maximum intensity peak (I_c), as given in Eq. 3:

$$\text{CI} = \{(I_c - I_{am})/I_c\} \times 100 \quad (3)$$

ATR-FTIR spectroscopy

Attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectroscopy of the samples (HC and RC) was performed at room temperature. The spectra were collected in the range of $450\text{--}4000\text{ cm}^{-1}$ as a result of 16 running scans at a resolution of 4 cm^{-1} , which provided information regarding the specific functional groups as well as the chemical structure.

FE-SEM analysis

Morphological characteristics of HC and RC were performed by a TESCAN MIRA3 (TESCAN; Brno, Czech Republic) field emission electron microscope (FE-SEM). Images of dried powdered samples were taken at different magnifications.

Parameter	Rice Straw	Banana Stem [33]	Hardwood [34]	Rice Straw [35]	Wheat Straw [36]
Solvent extractives, %	3.4	2.1	1.8±0.1	0.6	5.0
1% NaOH solubility, %	46.2	--	17.8±0.5	57.7	--
Hemicellulose, %	39.2	17.6	20.8±0.6	23 – 28	50
Cellulose, %	36.5	51.5	52.8±0.4	28 – 36	30
Holocellulose, %	66.6	69.8	--	--	--
Lignin, %	13.2	12.9	25.7±0.5	12 - 16	15
Ash, %	12.7	6.8	1.4±0.0	15-20	--
Silica content, %	7.6	--	--	9-14	--

II. Comparison of chemical constituent of woody and nonwoody raw materials.

Preparation of handsheets and measurement of physical properties

Bleached pulp (BP) of rice straw was created in the laboratory using a three-stage bleaching process with a dioxide, alkali-extraction, and dioxide (DED) sequence simulating industrial conditions. Bleached pulp was refined according to TAPPI T-248 so-00 “Laboratory beating of pulp (PFI mill method)” in a PFI mill to reach 500 CSF. Handsheets of four different blends were prepared; namely, 0, 5%, 10%, and 15% RC with BP coded as CP-1, CP-2, CP-3 and CP-4. The BP and RC were taken in different proportions and disintegrated in a disintegrator for about 10–15 min at a revolution of 3000 rpm. The stock of about 0.3% pulp consistency was prepared by diluting the pulp samples with tap water. The stock was then used for handsheet preparation of about 70±1 g/m² in a British sheet former. During handsheet preparation, the procedure was followed as per standard TAPPI T 205 sp-02 “Forming handsheets for physical tests of pulp.” The prepared handsheets were air dried overnight. Subsequently, for the measurement of physical properties such as tensile, burst, and tear index as per TAPPI T 220 sp-01 “Physical testing of pulp handsheets,” the air-dried handsheets were kept for conditioning at a temperature of 27±2°C and relative humidity of 65±2% for about 24 h as per ISO Standard Method 187:1990 “Paper, board and pulps — Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples.”

RESULTS AND DISCUSSION

Comparisons of chemical constituents of rice straw with other raw materials are shown in **Table II**. The HC is the total fraction of hemicelluloses and cellulose, which is found to be 75.5% in rice straw, comparable to that of hardwood (about 73.6%) and lower than that of wheat straw (80%). Rice straw pulps of about 53.2% yields were generated using the soda pulping process, and the HC was ex-

Pulping (Conditions: Bath Ratio = 1:4; Temperature = 165°C; Time at Temperature = 30 min)	
NaOH added, %	14.0
Unscreened pulp yield, %	53.4
Screen pulp yield, %	53.2
Extraction of Hollocellulose (Conditions: Temperature = 80°C; Time at Temperature = 3 h)	
Pulp taken, g	10
HC, g	9.6
Overall yield, %	51.1
Regenerated Cellulose (Conditions: Temperature = -10°C; Time = 12 h)	
HC taken, g	10.0
HC undissolved, g	5.8
RC obtained, g	4.2
Overall RC yield, %	21.5

III. Regenerated cellulose (RC) from rice straw (NaOH = sodium hydroxide).

tracted by removing lignin from the pulp. The overall yield of HC was about 51.1% of the raw material, and the results are depicted in **Table III**. About 42% of HC gets dissolved in a green solvent and converted into RC in a coagulation bath. It was proposed that the solubility of pulp depends on the α -cellulose content, with higher α -cellulose content resulting in higher solubility [37], and the α -cellulose content of rice straw is reported as 28%–36% [35]. Fiber deformation in terms of curls and kinked fiber is a very impor-

Parameters	HC	RC
Mean fiber length, mm	0.573	0.420
Mean fiber width, μm	15.1	18.3
Mean fiber coarseness, mg/m	0.019	0.709
Average kink number	1.4	1.3
Kinked fiber content, %	39.1	18.3
Mean fiber curl index, %	10.5	5.6
Fines content, millions/g of pulp	619.2	1139.9
Fines content, % in length	56.9	96.0
Mean fines length, μm	45	25
CED (viscosity), cP	7.5	3.2
Intrinsic viscosity (η), mL/g	315	220
Degree of polymerization	973	638
Solubility, %	42	--

IV. Fiber properties of holocellulose and regenerated cellulose.

tant characteristic, as kink refers to an abrupt change in the curvature and the direction of fiber and affects the strength properties, including tensile, tear, and burst [39]. For HC and RC, respectively, 39.1% and 18.3% of kinked fibers were observed (Table IV). The RC was observed with about a 5.6% curl index, which was much lower than that of the 10.5% curl index of HC. The fiber of HC was observed to have 56.9% fines element content, which was lower as compared to the 96% in RC. The main components of fines are cell debris, epidermal cells, and collenchymas cells [40], which can easily pass through a 200-mesh size screen. For the confirmation of fines content, CED viscosity for HC and RC was measured and found to be 7.5 and 3.2 cP, respectively, and the corresponding DP was 973 and 638, respectively, which refers to the number of glucose molecules per

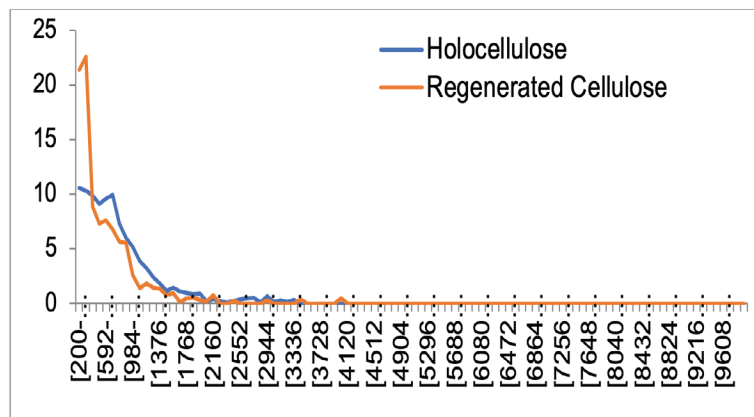
unit chain. It was clear that after the dissolution of cellulose in a solvent, a lower number of glucose molecules were precipitated during coagulation, and it has been well understood that mean fiber length is linearly dependent on the DP of cellulose [41].

Furthermore, the fiber length distribution is depicted in Table V, which shows that about 78% of the fiber fractions of HC are in the range of 0.2–1.0 mm in length, which nearly agrees with results reported by Rodriguez [38] where 72% of the fiber fractions of rice straw were reported in the same range. In the case of RC, it was observed that about 88.5% of fiber fractions were laid in that range, and the graphical presentation of fiber length distributions is shown in Fig. 3. Likewise, the fiber length distribution and fiber width distribution of HC and RC were carried out in the MorFi fiber analyzer, and the results are reported in Table VI. A width in the range of 5–17 μm was found for 72.7% of the HC fractions, and even with RC, 53.8% of fractions were found in this range. About 27.3% of HC fractions were found to be greater than 17 μm in width, while in the case of RC, about 46.2% of fractions were found greater than 17 μm in width. It was considered that, due to refining, all the mechanical properties except tear strength improved, and this is likely because fiber width increased by 65% and length shrunk by 20% after beating of fiber [42], and thereby the area of hydrogen bonding increased. Likewise, with beating of fiber, the regeneration process length of fiber was found to be reduced by 26.7% and the width increased by 21.2%. As expected from the data on fiber length distribution, the microscopic image of RC appears like small particles and that of HC appears as thread-like structures (Fig. 4), confirming a shorter fiber fraction for RC.

From XRD analysis, it was observed that the CI of RC gets reduced to 31% from 70.8%. It has been established that the CI of cellulose varies from 39% to 69%, depending on the technique used [43], and the low CI value of RC confirmed its amorphous structure. The XRD pattern of HC showed a sharp diffraction peak centered at $2\theta = 10.5^\circ$, as shown in Fig. 5, that might be due to the crystalline structure of cellulose; another broad peak centered at $2\theta = 30.0^\circ$

Fiber Distribution, size interval	HC, % on total fiber	RC, % on total fiber	Rodriguez, et al. [38], % on total fiber
0.2 – 0.5	30.8	52.9	46.0
0.5 – 1.0	47.2	35.6	26.0
1.0 – 1.5	12.5	6.9	14.0
1.5 – 2.0	5.3	2.5	6.0
2.0 – 2.5	1.2	1.4	4.0
2.5 – 3.0	2.2	0.4	4.0
3.0 – 3.5	0.9	0.4	0.0

V. Fiber length distribution.



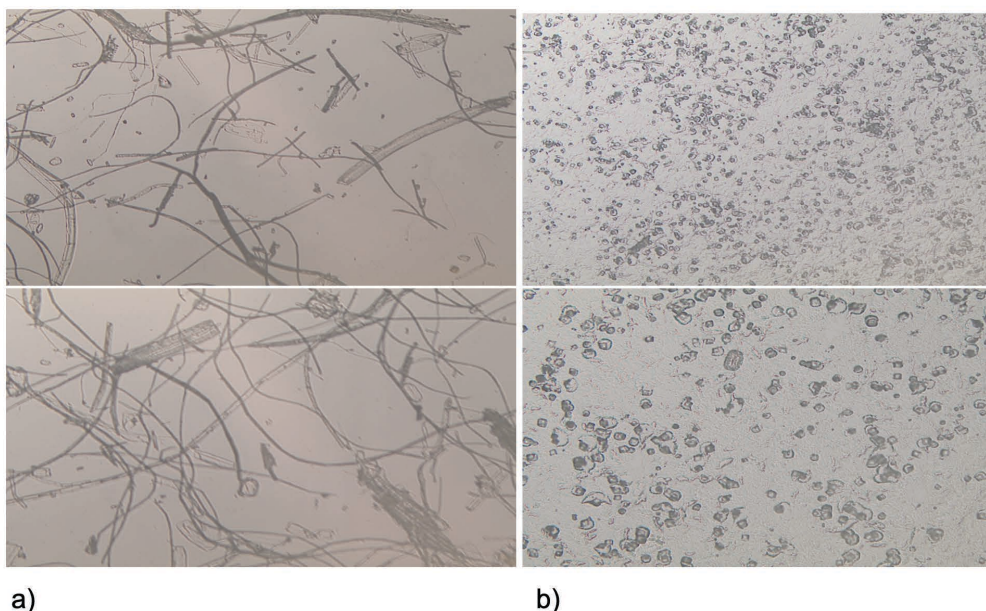
3. Graphical representation of fiber length distribution for holocellulose (HC) and regenerated cellulose (RC).

Fiber Width Distribution, (size interval, μm)	HC, % on total fiber	RC, % on total fiber
5 – 17	72.7	53.8
17 – 27	16.2	31.6
27 – 47	7.7	10.9
47 – 67	3.0	3.2
> 67	0.3	0.6

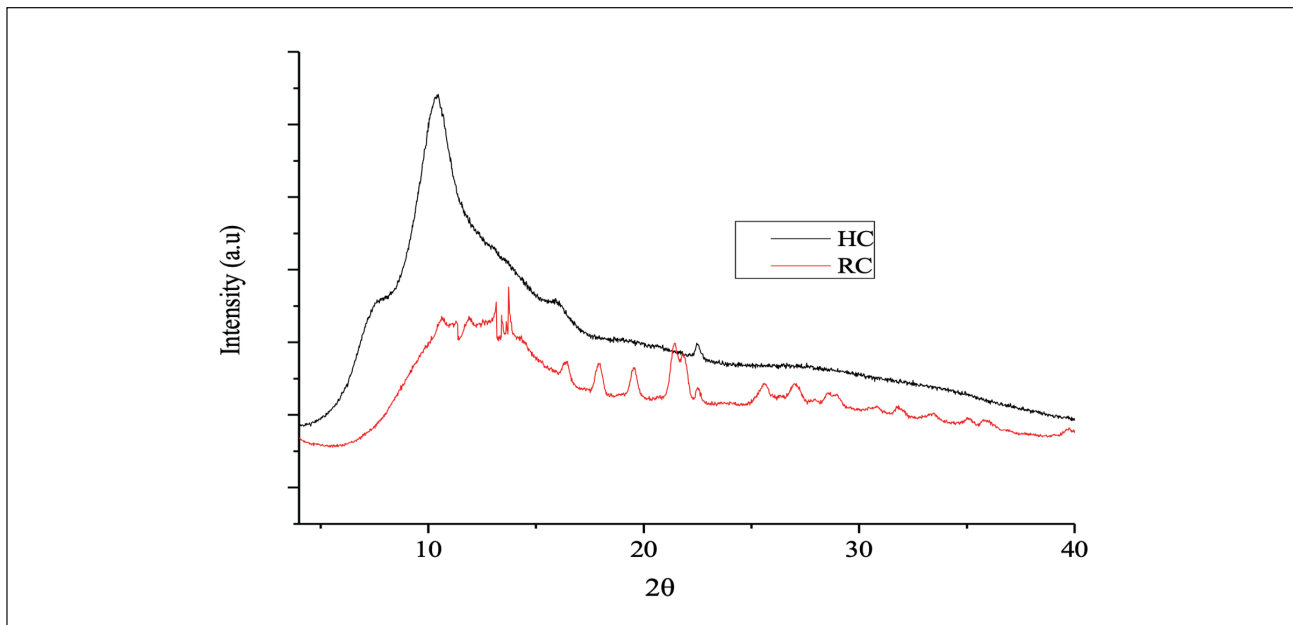
VI. Fiber width distribution.

was also observed, which confirmed the hemicelluloses content (amorphous structure) of the HC fraction. The amorphous peak at a different angle was seen in the XRD pattern of RC, which suggested that crystalline cellulose had been disrupted during dissolution in the solvent and became amorphized, showing broad peaks at 20.53° , 30.87° , and 80.9° [44].

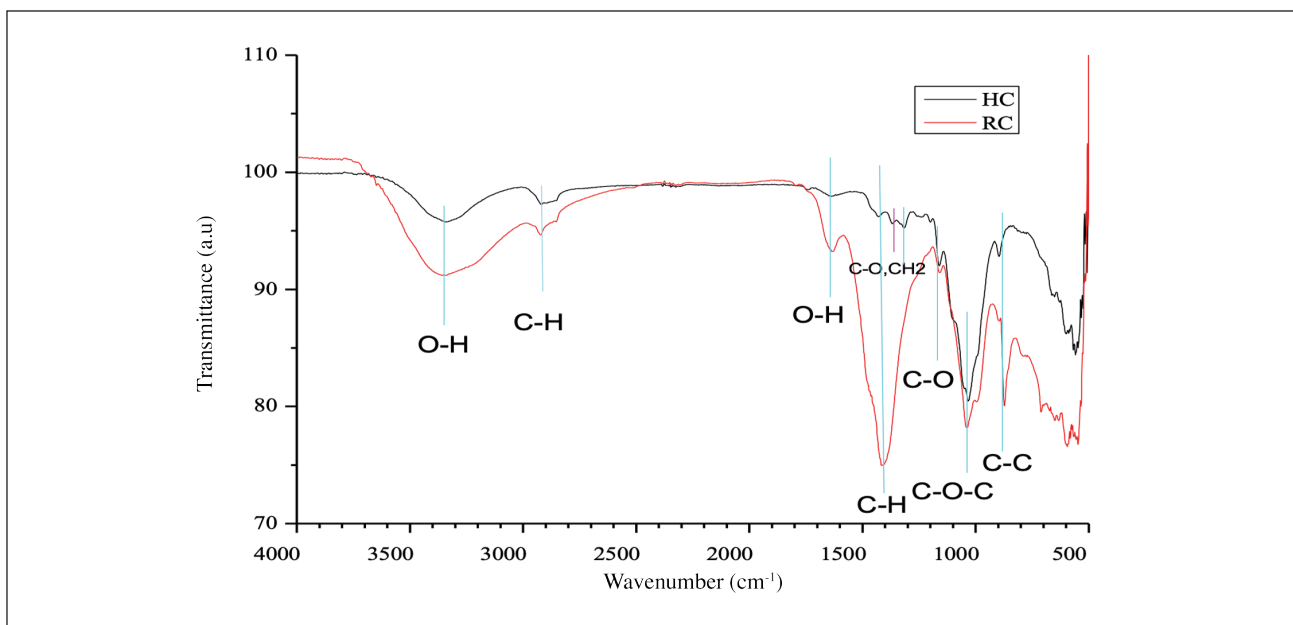
Infrared spectral characteristics of both HC and RC samples in the region of $4000\text{--}500\text{ cm}^{-1}$ are shown in **Fig. 6**. The similar characteristic peaks in samples demonstrated that very few changes in chemical structure were observed after dissolution in the solvent. However, some structural changes were observed, like a high-intensity absorption band in the region of $3300\text{--}3500\text{ cm}^{-1}$ for RC as compared



4. Optical microscopic image (magnification at 10x) of: a) HC, and b) RC.



5. X-ray diffraction patterns of HC and RC.

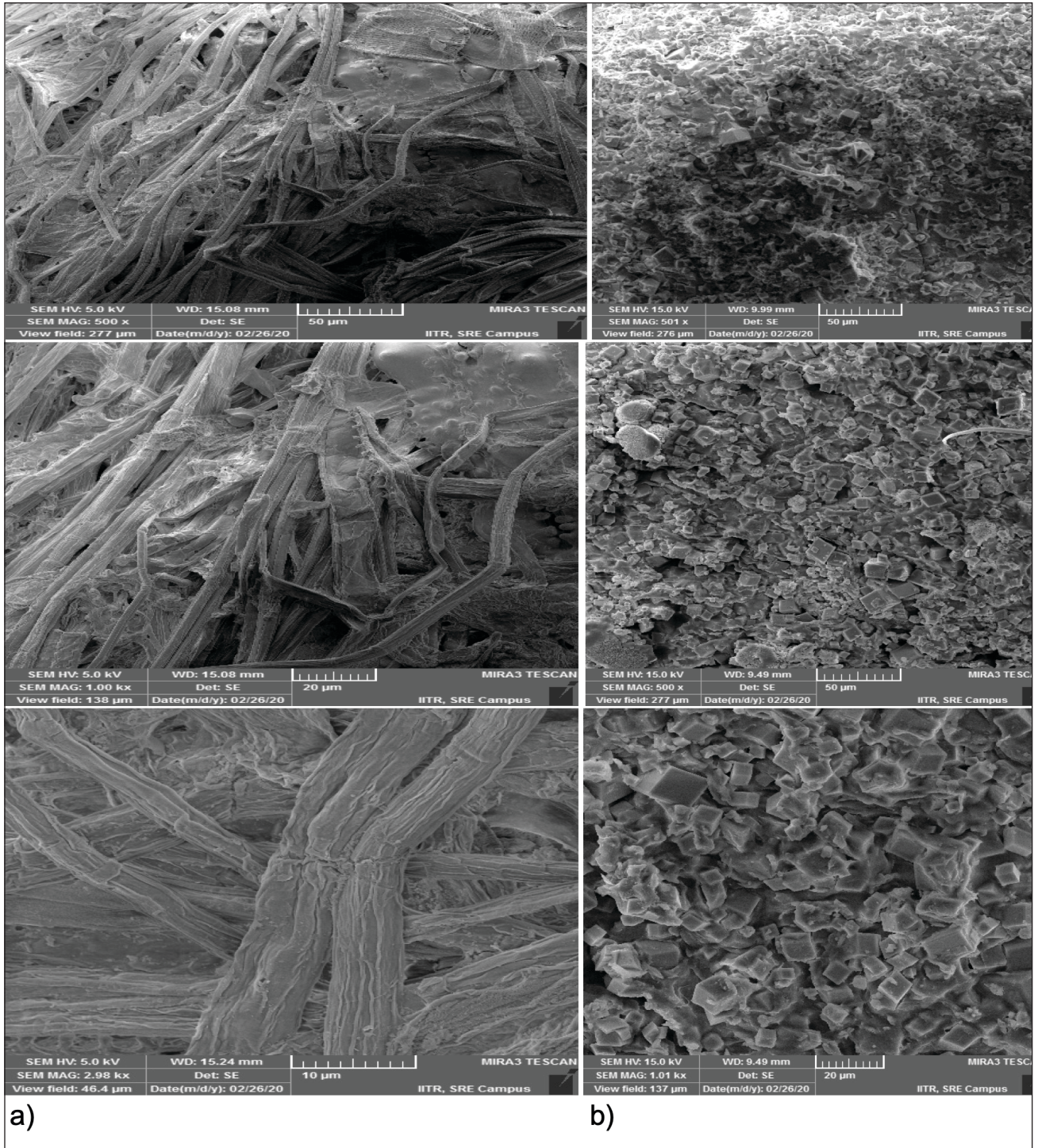


6. Fourier transform infrared (FTIR) patterns of HC and RC.

to HC, which indicated the presence of inter-hydrogen bonded -OH groups. A slightly high-intensity peak at 1400 cm^{-1} was observed in the spectra of RC, which again confirmed O-H stretching of RC, and another larger peak close to 1600 cm^{-1} and a peak near 900 cm^{-1} were observed in the spectra of RC. This finding represents the O-H bending of absorbed water [45], whereas a smaller peak at this band was observed for HC. It was also suggested that there was another peak around 1645 cm^{-1} , demonstrating the O-H bending of absorbed water [46,47]. Thus, ATR spectra confirmed that RC has greater concentration of hydroxyl groups in its chain than the HC chain does. Hydroxyl

groups in the cellulose ring contribute to the formation of inter- and intra-molecular hydrogen bonds. Formation of these kinds of bonds in the cellulose molecules not only has a great influence on the solubility [48,49] and hydroxyl reactivity [50,51], it also affects the mechanical properties of the cellulose [52]. So, the higher the -OH group, the higher are the chances of forming inter-fiber hydrogen bonding that ultimately will give high strength to the fiber network. From the results, it was observed that RC can be used as a strength additive in papermaking to enhance the physical properties of the paper.

From FE-SEM analysis of the samples, it was observed

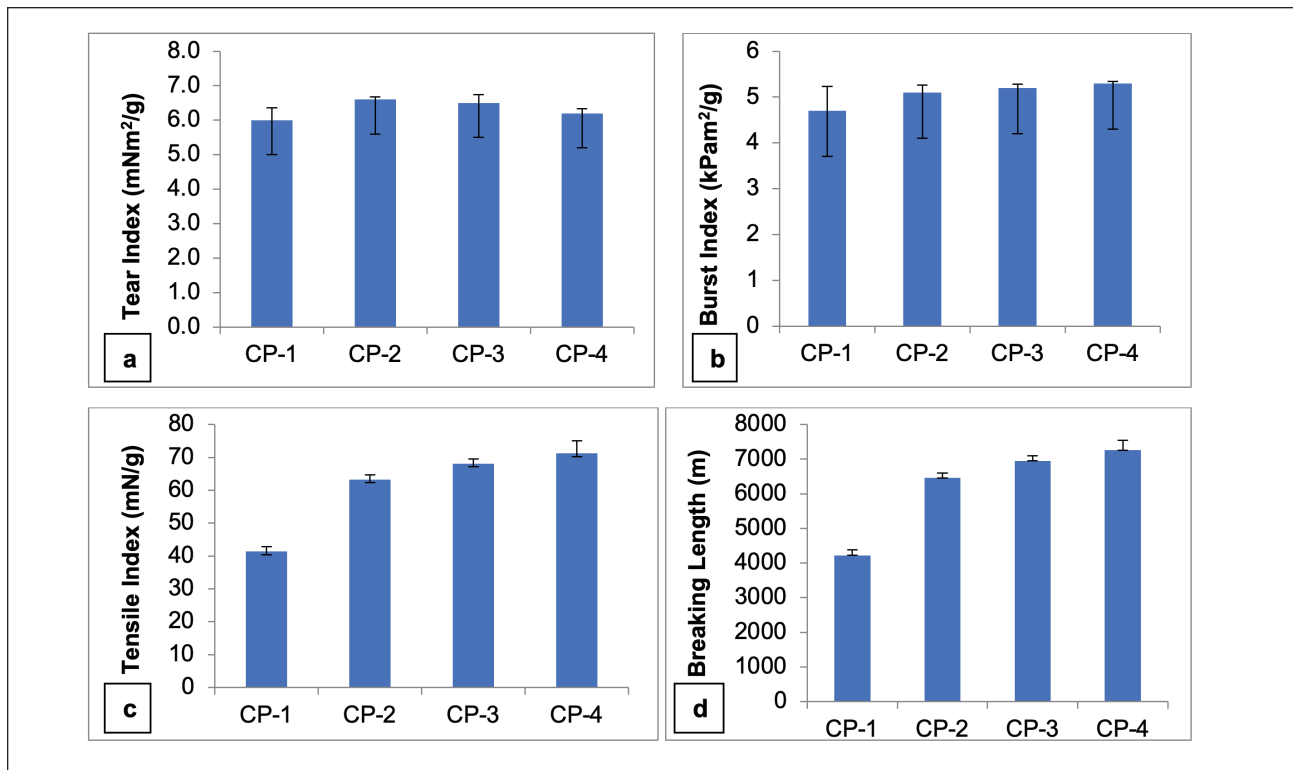


7. Field emission electron microscope (FE-SEM) image of: a) HC at magnification 500x, 1000x and 3000x; and b) RC at magnification 501x, 500x, and 1000x.

that fibers of HC appeared as skeletal rod-like structures having a bundle of nanofibers on their surface, and as suggested, nanofiber bundles were seen in the micro-size fiber of rice straw [53]; the RC was observed to have rectangular as well as circular cross-sections with the homogenous morphological and porous structures, as shown in **Fig. 7**. It has been verified that the structure of RC is largely in-

fluenced by the coagulation and stretching conditions of the regeneration process [54], and the RC film was observed to have a holey structure and several hydroxyl groups, which might serve as cavities forming the porous structure of RC [55].

Physical strength properties of composite paper (CP) of rice straw BP and RC were analyzed. As shown in **Fig. 8**,



8. Composite paper with different blends of RC: a) tear Index; b) burst index; c) tensile index; and d) tensile breaking length of paper.

the CP was found to have ultra-high tensile strength properties, which were enhanced from 41.4 N.m/g to 71.2 N.m/g with a 15% blend of RC. The tensile strength depends on the individual fiber, as well as the bonding between the fibers, and it was observed that RC has a high concentration of hydroxyl groups in its structure, which might help in forming a strong H-bond between the fibers. More hydroxyl groups promoted more inter-fiber hydrogen bonding, and thus with an increased percentage of RC in the blends, the tensile strength was found to have increased. Significant improvement in the burst index was observed from 4.7 kPa.m²/g to 5.3 kPa.m²/g with the addition of 5% to 15% of RC, but the tear index of paper was observed to have a slight improvement with up to 5% addition of RC, after which it was found to decline. The tear strength of paper depends on individual fiber behaviors [56] and is closely related to the length and strength of fibers [57].

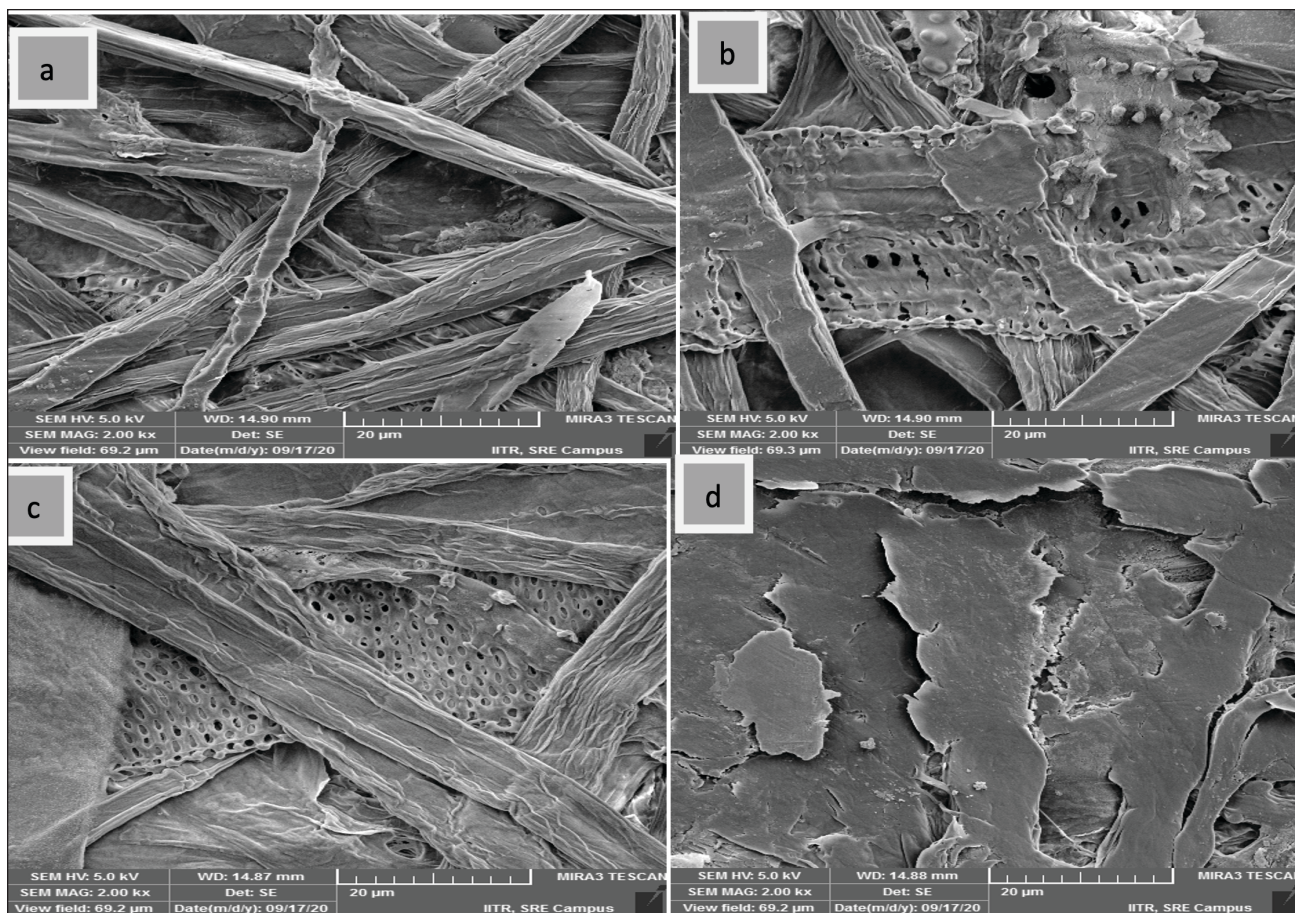
With beating/refining of the pulps, smaller fibers are generated and consequently, hydroxyl groups are increasingly separated from the surface of the fibers, improving the ability to bond between the fibers. In addition to that, an increasing number of small fibers fill the gap in the fiber network of the paper, which can weave the fibers, reduce the porosity, and improve the tensile as well as burst index of paper [58,59]. Studies have revealed that the curling of fiber is directly related to tensile strength [60,61] and that the removal of kinked fiber results in higher strength paper [62]. The RC was observed to have greater fiber width and a minimum percentage of kinked and curled fibers as com-

pare to the HC, which might enhance the physical properties of composite paper, especially for the tensile and burst index.

The FE-SEM analysis of CP that is shown in **Fig. 9a–9d** was carried out to see how the fiber network gets organized after blending BP with RC. As can be seen from the figure, RC significantly changed the morphological characteristics of that paper, and the spaces between the fibers in zero blend paper (Fig. 7a) got filled with RC (Fig. 9b–9d) and improved the crosslinking of fiber networks. This improved crosslinking of fiber networks might be the main cause of the improvement in the strength properties of CP. An effort has also been made to enhance the mechanical properties (ultra-high tensile strength) of paper by coating with RC [63].

CONCLUSIONS

Regenerated cellulose was prepared by using NaOH/urea/thiourea/water as a green solvent from paddy rice straw waste. The chemical structures of HC were almost unchanged, with a high concentration of hydroxyl groups in the chain of RC. Irrespective of having high fines element content in the resulting novel RC, a CP of rice straw BP with RC was developed with about 72% and 12.8% increase in the tensile index and burst index, respectively, with the addition of about 15% RC. A significant improvement in tear index of about 3.3% was observed with the addition of 5% RC, while it was found to decrease by further addition. Thus, rice straw waste can be expected as an alternative



9. The FE-SEM analysis of composite paper: a) CP-1; b) CP-2; c) CP-3; and d) CP-4.

source of cellulose-based fibrous raw material for the production of RC, which can be used as a strength additive to improve low mechanical properties for paper and paper-board requiring high tensile and burst strength. **TJ**

ACKNOWLEDGEMENTS

The authors are thankful to the head of the department of paper technology, IIT Roorkee, Saharanpur Campus. The authors are also very thankful to the laboratory staff, and chemical suppliers are gratefully acknowledged.

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ABOUT THIS PAPER

Cite this article as:

Alam, I., Kumar, J., and Sharma, C., *TAPPI J.* 20(7): 439(2021). <https://doi.org/10.32964/TJ20.7.439>

DOI: <https://doi.org/10.32964/TJ20.7.439>

ISSN: 0734-1415

Publisher: TAPPI Press

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We chose to study this topic because we wanted to use rice straw, which is a huge waste product in India, as a source of cellulose for producing regenerated cellulose (RC), which can be used as a strength additive for paper and paperboard. Preparation of RC from rice straw using a green solvent has not been done until this point, and use of RC as a papermaking additive to increase strength properties has also not been done before.

From this study, we saw that improvement in mechanical properties, especially tensile strength, is possible by adding RC. Our most surprising finding was that ultra-high tensile strength was possible in the composite paper made of a rice straw pulp blend with RC.

Agro-based industries are challenged by low physical properties of products, and using RC as an additive has potential for improving them. Our next step will be utilization of RC as a coating material



Alam



Kumar



Sharma

to improve barrier properties of paper and recycling of effluents.

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