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DISSOLVING PULP FROM NON-WOOD FEEDSTOCKS: AN ALTERNATIVE PATHWAY TOWARD OBTAINING ENGINEERED SUSTAINABLE FIBERS FOR TEXTILE APPLICATIONS.

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SUMMARY

This study evaluates non-wood fibers such as wheat straw, switchgrass, and hemp hurd as potential alternatives for producing dissolving pulp using sulfur-ethanol-water (SEW) pulping. The SEW process was optimized for wheat straw, and the optimum pulping conditions were 130ºC, 4h, and 10% SO2 concentration, resulting in a viscose-grade pulp with 93% α-cellulose, 2.0% hemicellulose, <0.1% lignin, and 0.2% ash content. The best pulping conditions for wheat straw were applied to switchgrass and hemp hurd. The results showed that both wheat straw and switchgrass had similar pulp quality, while hemp hurd had a higher hemicellulose content and lower viscosity. Dissolving pulp was used to obtain engineered fibers via low chemical and non-solvent spinning processes. This work suggests that non-wood feedstocks such as wheat straw and switchgrass can be promising alternatives for dissolving pulp and spun fiber production, which can help reduce the pressure on the textile industry to increase the use of natural fibers and mitigate the environmental impact of non-biodegradable synthetic fibers.

Keywords: Alternative fibers, SEW, Dissolving Pulp, Textiles, Sustainability.

INTRODUCTION

In 2021, global textile fiber production reached approximately 100 million metric tons, with non-biodegradable, petroleum-based fibers dominating the market and accounting for around 65% of total production[1]. After cotton, cellulosic man-made fibers such as viscose, and lyocell are the main source of natural fibers, which are produced from dissolving pulp (DSP) processes [2]. DSP refers to a pulp with a high content of cellulose (>90%), and low amounts of lignin (<0.1%), hemicelluloses (<2.5%), and ash (<0.1%). Matching these requirements, DSP is suitable for dissolving, regeneration and fiber spinning for textile production [3]. However, cotton production has reached its maximal capacity and declined 4.1% during 2012-2013 due to the shrinkage of cotton growing land[4]. With population growth, estimated market shortage of native cellulosic textile fibers is at least 1.7 Kg per capita by 2030 [5]. Thus, it is essential to implement alternative natural fiber sources that can replace and compete with current market fibers in terms of price, performance, and environmental footprint, especially in the case of synthetic fibers, which have a significant carbon footprint associated with their use.

With more than ten thousand million tons of lignocellulosic agricultural residues produced worldwide (e.g., wheat straw), in addition to the potential utilization of purposely planted feedstock (e.g., bamboo, or switchgrass) or agro-industrial residues (e.g., sugarcane bagasse or hemp hurd) [6], non-woody biomass represent a viable feedstock alternative to produce cellulosic engineered fibers for use in the textile industry (Fig. 1). However, unlike wood, these alternative feedstocks are not compatible with the industry standard processes (e.g., Kraft) due to their high content of silica, which dissolves in the liquor during pulping and causes scaling problems downstream in the conversion process [6]. Different pulping methods such as Organosolvs are emerging since they possess simpler chemical recovery systems [7]. SO_2-Ethanol-Water (SEW) pulping is one of such processes, where the dissolution of lignin is catalyzed by the SO_2, promoting alpha-cleavages while the ethanol increases the solubility of both sulfonated and non-sulfonated lignin and to prevent acid-catalyzed condensation reactions [8].

The SEW fractionation process is a type of organosolv process that is used in biorefinery systems to create a variety of high-value products, such as pulp, paper, lignosulfonates, and biofuels [6]. The SEW pulping facilitates faster and easier recovery of chemicals through distillation, due to the presence of fractionation chemicals such as ethanol and unreacted SO_2 [9]. The SEW process produces a high-quality, easy-to-bleach dissolving pulp while generating high-purity spent liquor [9]. In addition, it retains the carbohydrates in the pulping liquor, creating easy-to-recover monosaccharides that are ideal for biorefinery purposes like biofuels and green chemicals[10].

This work highlights the potential of three non-wood feedstocks, namely wheat straw, switchgrass, and hemp hurd for dissolving pulp applications, particularly viscose-grade pulp, as an alternative to petroleum based, synthetic material. To achieve this, a sulfur-ethanol-water (SEW) pulping process has been implemented, where the effect of pulping parameters on pulp quality is also evaluated. The successful production of dissolving pulp from non-wood biomass aligns with the objective of promoting sustainable textile production and reducing the reliance on synthetic fibers in the textile industry.

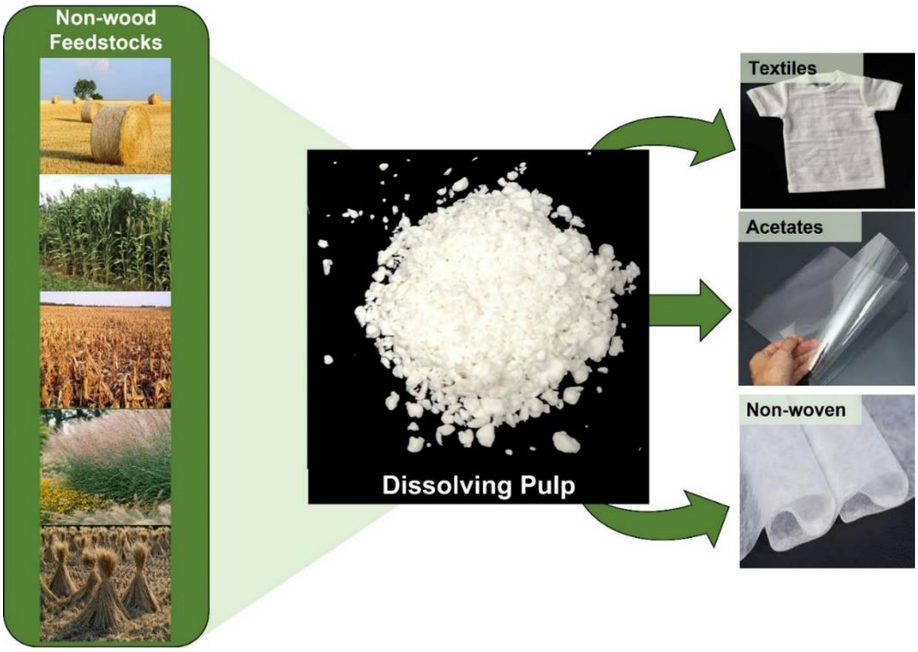

Figure 1. Nonwood feedstock as alternative and potential source for dissolving pulp production toward textile applications.

EXPERIMENTAL

Materials

Wheat straw (Ag. Processing Solutions Inc., Montana), Switchgrass (Genera Inc, Tennessee) and Hemp Hurd (Ag. Processing Solutions Inc., Montana) were used as non-wood feedstock for SEW pulping. Chemical characterization of the feedstocks including benzene-ethanol extractives and primary chemical components were assessed according to TAPPI T207, and TAPPI T204 respectively. All the feedstocks were hammer milled and screened prior to the chemical composition analysis. The α-cellulose and hemicellulose contents were determined according to the National Renewable Energy Laboratory (NREL) standard methods (Sluiter et al., 2008). Lignin and ash content was estimated by following the TAPPI T 222 om-02 standard method. SO2 gas (99% purity, Millipore Sigma, USA), Reagent alcohol (99% purity, Fisher scientific, USA) and Deionized (DI) water were used for the SEW liquor.

Methods

Sulfur-ethanol-water pulping

The SEW pulping liquor was comprised by SO2-Ethanol-Water at a ratio 10-45-45 wt.% respectively. To achieve that composition, an ethanol-water solution was first prepared at a 50-50wt.% ratio and placed overnight into the freezer to ensure temperatures close to 0 ºC degrees. Low temperatures facilitated the adsorption of the SO2 gas, which was bubbled into the ethanol-water solution. The pulping was assessed in a laboratory rotary digester (Model: SKZ1021, China) at a 10:1 liquor-to-wood ratio for 300 oven-dried (O.D) grams of biomass. Pulping temperature was evaluated in a range between 100 and 135 ºC while pulping time was performed over a range of 1-4 hours. The main pulping assessment was evaluated on wheat straw. Then, the best pulping conditions for wheat straw were applied to the other two feedstocks.

Alkaline extraction post-treatment.

The SEW pulp was immersed in a 2% NaOH solution at a liquor-to -wood ratio of 10:1 at 70 °C for 1 h. After extraction, the pulp was washed, collected, centrifuged, and stored at 4 °C for subsequent experiments and analyses.

Pulp bleaching.

A chlorine dioxide (D) bleaching sequence was considered to bleach the SEW pulp after alkaline extraction (E). The bleaching was a D_0ED_1 sequence where the D_0 stage was carried out with chlorine dioxide under a kappa factor of 0.25, a liquor-to-wood ratio of 10:1, 70 °C and 1 hour. The E stage was an alkaline extraction as described in section 2.2.2. Lastly, the D_1 stage was carried out at a ClO_2 charge of 0.16% based on the O.D mass at a liquor-to-wood ratio of 10:1, 70 °C, and 1 hour.

Pulp characterization and chemical composition.

Pulp was characterized after SEW pulping, alkaline extraction and bleaching respectively. Kappa number, viscosity, brightness, S10, and S18 were tested according to TAPPI T236, TAPPI T230, TAPPI T203, and TAPPI T452 standards, respectively. The composition of the SEW pulp was tracked in all the processes to obtain the dissolving pulp grade (including pulping, alkaline extraction, and bleaching). The pulps' chemical composition was analyzed using the NREL standard method [11]. Monomeric sugars such as glucose and xylose were measured using a high-performance liquid chromatography (HPLC) system (1200; Agilent Technologies Inc., Santa Clara, CA, USA) to estimate the αcellulose and hemicelluloses content in the pulp.

RESULTS AND DISCUSSION

Feedstock characterization

The breakdown of the chemical composition of raw wheat straw, switchgrass, and hemp hurd is shown in Fig. 2. It can be noticed that all feedstocks have a high content of ash, within a range of 2.9 to 5% ash content, wheat straw being the one with the highest ash content. In general, the feedstocks have α-cellulose (represented as glucose) and lignin content around 35 and 25 wt.% respectively. There is a significant difference regarding the hemicelluloses content, represented by the summation of xylose, mannose, and arabinose. While wheat straw contains 22.1 wt.% of hemicelluloses, switchgrass and hemp hurd contain 23.1 and 23.3wt.%, respectively. The content of Benzene-ethanol extractives from the feedstocks were 5.4, 4.5, and 3.7wt.% for wheat straw, hemp hurd and switchgrass, respectively.

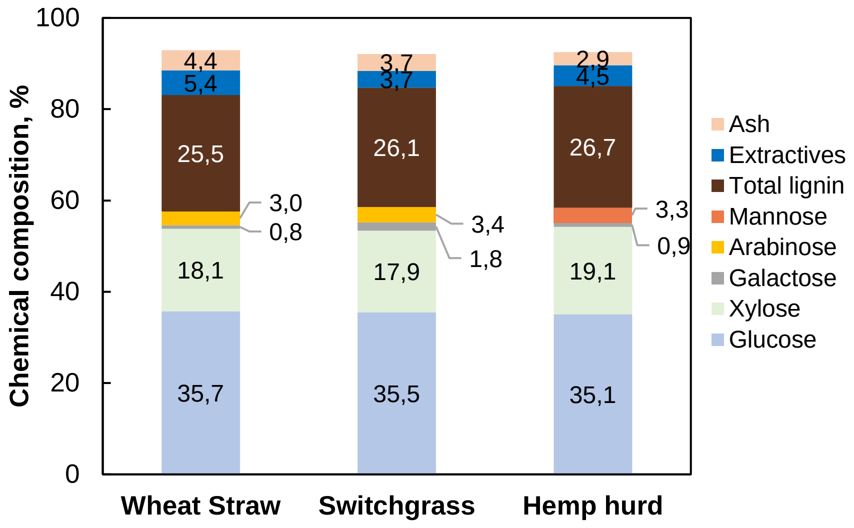

Figure 2. Chemical composition of wheat straw, switchgrass, and hemp hurd.

SEW pulping for wheat straw.

This section shows a systematic assessment of SEW pulping for wheat straw; results are summarized in Table 1 for twelve SEW trials. Table 1 shows the effect of the temperature and pulping time on the pulping yield, kappa, and viscosity. Pulping performance and pulp characteristics (chemical composition, kappa, and viscosity) seem to be highly sensitive to the temperature and time evaluated in the range of 100-130 ºC and 1-4h, respectively. Total yield, kappa, and viscosity are observed to decrease with the increase in temperature or time. Total yield is observed to be between 58 and 35% in the evaluated range of temperature and pulping time. The decrease in yield is expected due to higher delignification, also reflected by a decrease in kappa number. Kappa is kept constant after 120 ºC and 2 hours of pulping, while a dramatic decrease in viscosity is observed at 130 ºC after 2 hours of pulping. The decrease in viscosity is related to the hydrolysis of carbohydrates (especially hemicelluloses) under acidic conditions in the SEW pulping (pH~2.5). Thus, carbohydrates are depolymerized, which also contributes to a decrease in the molecular weight distribution of the pulp, reflected by a decrease in viscosity [12].

Table 1. Characterization and chemical composition of wheat straw after SEW pulping.

	Pulping Conditions SO_2-Ethanol-Water (10-45-45%wt.)		**Unbleached Pulp characterization**				**Chemical Composition, %**			
Trial	Temperature, °C	Time, h	Total yield, %	Kappa	ISO Brightness	Viscosity, Cp	Lignin,%	Cellulose,%	Hemicellulose,%	Ash,%
SEW1	100	1	58	35	33.1	19.8	13.8	60.1	13.9	3.9
SEW2	110	1	57	34	34.7	17.6	13.3	60.5	13.7	3.7
SEW3	120	1	53	22	40.5	15.1	11.5	64.6	13.3	3.5
SEW4	130	1	46	13	44.2	11.3	10.2	66.9	12.6	3.3
SEW5	100	2	57	25	39.6	16.4	12.9	62.3	13.2	3.5
SEW6	110	2	55	22	41.9	15.5	12.1	62.9	13.6	2.4
SEW7	120	2	46	11	46.3	14.6	6.4	70.8	11.9	3.2
SEW8	130	2	41	9	55.3	7.4	4.9	74.6	9.8	3.2
SEW9	100	4	46	12	49.0	15.7	7.4	70.1	11.9	3.4
SEW10	110	4	44	9.6	53.0	14.1	6.6	73.3	10.2	2.9
SEW11	120	4	40	8	57.5	13.6	3.7	77.7	8.1	2.3
SEW12	130	4	34	7	57.0	4.9	2.3	83.7	2.9	2.2

a) pH of white liquor: 2.5; b) pH of black liquor: below 1.5; c) No lignin condensation was observed in the evaluated range of temperature and time. d) Trial 11 and 12 are selected for alkaline extraction and bleaching treatments.

Based on the viscose-grade criteria, experimental results, the best pulping conditions for wheat straw were 130 ºC and 4 hours of pulping (SEW12 trial). However, after pulping, lignin and ash composition are still high and further post-treatments must be carried out to minimize these undesired components in the pulp. Thus, alkaline extraction and D0ED1 bleaching were performed, which results are shown in the next sections for pulp obtained in SEW12. On the other hand, pulp from SEW11 trial containing high hemicellulose content was also chosen to better evaluate the purification performance of these post-treatments on SEW pulp.

Alkaline extraction

Table 2 shows that alkaline extraction had an important effect on reducing lignin, and ash in wheat straw pulp. However, this post-treatment was not effective enough to reduce the hemicellulose content, i.e., from 8.1% to 7.9% for SEW11 and from 2.9% to 2.3% for SEW12 pulp. Considering that the alkaline extraction was assessed at a 2% NaOH charge (based on dry mass), higher charges of NaOH are expected to extract more hemicelluloses at the expense process economics. A good example is the cold caustic extraction that uses chemical charges of NaOH up to 18% [13]. However, these high alkaline conditions were not evaluated in this work to avoid the possible modification of cellulose from cellulose I to cellulose II, negatively affecting the reactivity of the pulp. Previous work has reported the negative effect of cellulose II on some dissolving and regeneration process at viscose-grade levels (e.g., Lyocell process) [13].

Pulp Bleaching

After Alkaline extraction, a D_0ED_1 bleaching sequence was assessed for both SEW11 and SEW12 pulps. Figure 3 shows the pulping sequence particularly for SEW12 trial, where a white pulp is obtained, related to a full delignification (Table 2). After bleaching, a decrease in the ash content to 0.2% for both SEW11 and SEW12 was also observed, which can be associated with the alkaline extraction stage (E stage) able to solubilize more ash from the pulp. The bleaching sequence did not extract xylose in a representative way, but it is important to mention that, after bleaching, SEW12 pulp is the most suitable for viscose-grade applications due to having the lowest impurities, namely hemicellulose (2.1%), lignin (<0.1%), and ash content (0.2%), as shown in table 2.

Table 2. Pulp characterization after pulping, alkaline extraction and D_0ED_1 bleaching.

After pulping								
Trial	**Pulp characterization**				**Chemical composition, %**			
	Pulping yield, %	Kappa	ISO Brightness, %	Viscosity, Cp	Lignin,%	Cellulose,%	Hemicellulose,%	Ash,%
SEW11	40	8	57.5	13.6	3.7	77.7	8.1	2.3
SEW12	34	7	57.0	4.9	2.3	83.7	2.9	2.2
After Alkaline Extraction								
Trial	**Pulp characterization**				**Chemical composition, %**			
	AE yield %	Kappa	ISO Brightness, %	Viscosity, Cp	Lignin,%	Cellulose,%	Hemicellulose,%	Ash,%
SEW11	97	5	70.3	15.5	2.6	81.6	7.9	1.1
SEW12	98	5	71.4	4.7	2.1	90.0	2.3	0.8
After D_0ED_1 Bleaching								
Trial	**Pulp characterization**				**Chemical composition, %**			
	Bleaching yield %	Kappa	ISO Brightness, %	Viscosity, Cp	Lignin,%	Cellulose,%	Hemicellulose,%	Ash,%
SEW11	98	N/A	90	14.4	<0.1	84.7	7.1	0.2
SEW12	98	N/A	91	4.7	<0.1	92.8	2.0	0.2

Comparison of wheat straw with other non-wood feedstocks.

While it is acknowledged that the optimal conditions for pulping wheat straw may not apply to other feedstocks, the SEW12 treatment conditions were implemented in processing two other alternative non-wood sources, namely switchgrass and hemp hurd. Table 3 summarizes the pulp characterization and final chemical composition for all three feedstocks after pulping, alkaline extraction, and bleaching. Table 3 shows that obtaining pulps with minimal hemicellulose content was possible for wheat straw and switchgrass but not for hemp hurd, which had important differences in pulp quality. S10 and S18 values are also shown in Table 2, which are two important quality indicator parameters for dissolving pulp. S10 refers to quantifying the percentage of carbohydrates soluble in a 10% NaOH solution. Under these conditions, both hemicelluloses and low molecular weight cellulose are expected to dissolve, considering that at 10%wt NaOH concentration occurs, the maximum swelling of cellulose [13]. S18 refers to the percentage of carbohydrates soluble in 18% NaOH solution, which is only hemicelluloses. Thus, S18 is an approximation of the hemicellulose content of the pulp. The lower the S10 and S18 values, the higher the quality of the dissolving pulp [13]. S18 is usually lower than S10 values, and the difference between S10 – S18 shows approximately the fraction of the dissolving pulp that could be lost in viscose dissolving and regeneration processes [14]. Switchgrass was shown to be the feedstock with the lowest S10 and S18 values while hemp hurd was the one with the highest values. Differences can be attributed to the nature of the feedstock, including species, anatomical structure, and morphology that influence the ease of the feedstocks to be pulped [11].

S10-S18 values show the potential of having diminished yields during subsequent dissolving, regeneration, and spinning procedures (such as the viscose or lyocell process) in textile making processes. Compared to both wheat straw and switchgrass, hemp hurd exhibited significantly higher S10-S18 values, which could challenge its quality for dissolving pulp application. On the other hand, wheat straw and switchgrass show a promising avenue for utilization in textile production due to having high purities (very low hemicellulose content) and reasonable S10 and S18 values [14].

Regarding viscosity, switchgrass showed a slightly higher viscosity than wheat straw. On the other hand, hemp hurd had the lowest viscosity which could be attributed to a lower degree of polymerization after pulping. The effect of viscosity on pulp quality is subjected to meet spinning process criteria. Beyond chemical composition requirements succeeded in this work, degree of polymerization (related to the viscosity) requirements changes based on the type of spinning process. For example, lyocell process requires DP about 550-650 while Viscose (rayon) process requires about 450-750 [15]. Thus, future assessment will be focused on identifying spinning processes suitable for the non-wood dissolving pulp obtained in this work.

Table 3. Comparison of non-wood dissolving pulp.

Pulp	**Pulp characterization**						**Chemical composition, %**			
	Total yield, %	ISO Brightness	Viscosity, Cp	S10	S18	S10-S18	Lignin,%	Cellulose,%	Hemicellulose,%	Ash,%
Wheat Straw	33	91	4.7	11.3	3.1	8.2	<0.1	92.8	2.0	0.2
Switchgrass	34	89	5.3	9.8	2.9	6.9	<0.1	93.7	2.4	0.2
Hemp Hurd	39	89	2.2*	18.7	7.6	12.7	<0.1	91.1	4.1	0.1

* Might be out appreciation scale of the viscometer.

Challenges and Opportunities

Non-wood feedstocks are emerging as an alternative source to produce dissolving grade pulp for multiple applications, with a major interest in textiles. Perennial grasses, agricultural residues, and agro-industrial residues such as wheat straw, hemp, and switchgrass are presented in this work as alternative feedstock to produce dissolving-grade pulps with viscose-grade features. However, from a technical point of view, one of the main issues to pulping these types of raw materials is related to the high ash content, challenging the conventional pulping and chemical recovery methods [6]. Thus, alternative pulping methods such as SEW emerged to make chemical recovery processes more affordable for these raw materials. The results of this study suggest that the production of dissolving pulp from non-wood feedstocks offers a good opportunity to increase the supply of natural fibers in the textile industry (Fig.3). From an economic point standpoint, challenges persist, mainly related to the supply of non-wood feedstocks, which could make it difficult to have facilities with high production rates. Another existing challenge is the still high content of ash of non-wood pulps, which could limit their use to viscose-grade applications. Acetate grades would need pulps with even higher purity. However, applying chemical treatments (e.g., chelating agents) could be helpful in reaching ash content below 0.2%.

Regarding opportunities, the development of feasible processes to convert non-wood feedstocks into dissolving pulp would increase the profit of farmers and processing facilities that have non-wood materials as wastes or secondary products, which is the case for wheat straw or hemp hurd. From an environmental point of view, the adoption of non-wood fibers can also make a significant contribution. Feedstocks like switchgrass can sequester high contents of CO_2 in the soil during farming, making them a raw material with a lower carbon footprint [16]. More importantly, the role of non-wood sources in increasing the production of natural man-made fibers and decreasing the market share of synthetic fibers (e.g., polyester) in the textile industry is the main environmental contribution of these non-woody biomasses. A significant reduction in using these synthetic fibers would be beneficial in reducing non-biodegradable fibers that also represent a significant share in the detrimental microplastic generation, and textile landfilling [1].

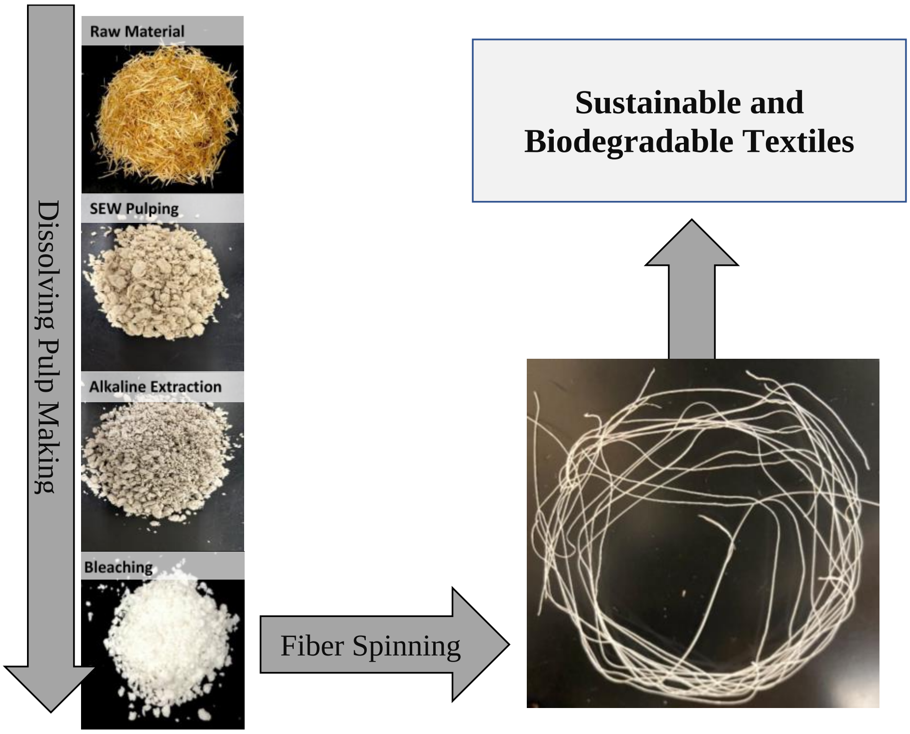

Figure 3. Schematic conversion sequence of pulping, alkaline extraction, and D0ED1 bleaching for converting wheat straw into dissolving pulp and its potential for fiber spinning and textile making.

CONCLUSIONS

Dissolving pulp was obtained from wheat straw, switchgrass, and hemp hurd using SEW pulping. The best conditions for wheat straw were found to be at 130C for 4 hours, then applied to switchgrass and hemp hurd. SEW pulping produced non-wood pulp with acceptable hemicellulose content for viscose-grade pulp and over 90% cellulose content after bleaching post-treatments. Although switchgrass and wheat straw had similar pulp quality suitable for viscose-grade dissolving pulp, hemp hurd had higher hemicellulose content and the lowest pulp quality, making it challenging for dissolving pulp applications. Utilizing alternative fibers from non-wood biomass offers an opportunity for eco-friendly textile products that meet environment and sustainability-oriented consumer's demands toward fighting climate change.

REFERENCES

[1] R. E. Vera *et al.*, "Transforming textile wastes into biobased building blocks via enzymatic hydrolysis: A review of key challenges and opportunities," *Cleaner and Circular Bioeconomy*, vol. 3, p. 100026, Dec. 2022, doi: 10.1016/J.CLCB.2022.100026.

[2] C. Felgueiras, N. G. Azoia, C. Gonçalves, M. Gama, and F. Dourado, "Trends on the Cellulose-Based Textiles: Raw Materials and Technologies," *Frontiers in Bioengineering and Biotechnology*, vol. 9. Frontiers Media S.A., Mar. 29, 2021. doi: 10.3389/fbioe.2021.608826.

[3] W. Liu, S. Liu, T. Liu, T. Liu, J. Zhang, and H. Liu, "Eco-friendly post-consumer cotton waste recycling for regenerated cellulose fibers," *Carbohydr Polym*, vol. 206, no. October 2018, pp. 141–148, 2019, doi: 10.1016/j.carbpol.2018.10.046.

[4] Y. Ma, M. Hummel, M. Määttänen, A. Särkilahti, A. Harlin, and H. Sixta, "Upcycling of waste paper and cardboard to textiles †," *Green Chemistry*, vol. 18, p. 858, 2016, doi: 10.1039/c5gc01679g.

[5] L. K. J. Hauru *et al.*, "Enhancement of ionic liquid-aided fractionation of birchwood. Part 1: autohydrolysis pretreatment," *RSC Adv*, vol. 3, no. 37, pp. 16365–16373, Aug. 2013, doi: 10.1039/C3RA41529E.

[6] M. S. Jahan, M. M. Rahman, and Y. Ni, "Alternative initiatives for non-wood chemical pulping and integration with the biorefinery concept: A review," *Biofuels, Bioproducts and Biorefining*, vol. 15, no. 1. John Wiley and Sons Ltd, pp. 100–118, Jan. 01, 2021. doi: 10.1002/bbb.2143.

[7] R. Yadollahi *et al.*, "SO2–ethanol–water (SEW) and kraft pulping of giant milkweed (Calotropis procera) for cellulose acetate film production," *Cellulose*, vol. 25, no. 6, pp. 3281–3294, Jun. 2018, doi: 10.1007/S10570-018-1802-7/FIGURES/7.

[8] A. Rodríguez *et al.*, "Different Solvents for Organosolv Pulping," *Pulp and Paper Processing*, Oct. 2018, doi: 10.5772/INTECHOPEN.79015.

[9] M. Iakovlev, X. You, A. van Heiningen, and H. Sixta, "SO2-ethanol-water (SEW) fractionation process: Production of dissolving pulp from spruce," *Cellulose*, vol. 21, no. 3, pp. 1419–1429, 2014, doi: 10.1007/s10570-014-0202-x.

[10] M. D. Firouzabadi and A. Tatari, "SO2-ethanol–water (SEW) and Kraft pulp and paper properties of Eldar pine (Pinus eldarica): a comparison study," *Biomass Convers Biorefin*, vol. 1, pp. 1–9, Jan. 2023, doi: 10.1007/S13399-023-03785-X/TABLES/7.

[11] C. Huang, R. Sun, H. M. Chang, Q. Yong, H. Jameel, and R. Phillips, "Production of dissolving grade pulp from tobacco stalk through SO2-ethanol-water fractionation, alkaline extraction, and bleaching processes," *Bioresources*, vol. 14, no. 3, pp. 5544–5558, 2019, doi: 10.15376/BIORES.14.3.5544-5558.

[12] K. Thielemans *et al.*, "Decreasing the degree of polymerization of microcrystalline cellulose by mechanical impact and acid hydrolysis," *Carbohydr Polym*, vol. 294, p. 119764, Oct. 2022, doi: 10.1016/J.CARBPOL.2022.119764.

[13] X. Dou and Y. Tang, "The Influence of Cold Caustic Extraction on the Purity, Accessibility and Reactivity of Dissolving-Grade Pulp," *ChemistrySelect*, vol. 2, no. 35, pp. 11462–11468, Dec. 2017, doi: 10.1002/SLCT.201701551.

[14] S. A. 1923- Rydholm, "Pulping processes.," p. 1269, 1965, Accessed: Oct. 03, 2022. [Online]. Available: https://books.google.com/books/about/Pulping_Processes.html?id=dSrfuQEACAAJ

[15] M. C. Biswas, R. Dwyer, J. Jimenez, H.-C. Su, and E. Ford, "Strengthening Regenerated Cellulose Fibers Sourced from Recycled Cotton T-Shirt Using Glucaric Acid for Antiplasticization," *Polysaccharides 2021, Vol. 2, Pages 138-153*, vol. 2, no. 1, pp. 138–153, Mar. 2021, doi: 10.3390/POLYSACCHARIDES2010010.

[16] J. Bai *et al.*, "Effects of Biofuel Crop Switchgrass (Panicum virgatum) Cultivation on Soil Carbon Sequestration and Greenhouse Gas Emissions: A Review," *Life 2022, Vol. 12, Page 2105*, vol. 12, no. 12, p. 2105, Dec. 2022, doi: 10.3390/LIFE12122105.