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Influence of pulping conditions on rice straw kraft pulp yield and screened rejects

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Abstract

Although wood is the primary raw material for pulp and paper manufacturing, there is a growing interest in non-woody raw materials to meet the increasing demand of paper. Non-woody biomass rice straw is geographically abundant in South Asia which can be used as a potential raw material for pulp and paper production due to less chemical and shorter cooking time required in pulping process. The objective of this study was to investigate the effect of temperature and active alkali concentration (Na+) on pulp yield (%) and screened rejects (%) during the kraft pulping of rice straw. The kraft pulping was carried out at 15:1 liquor-to-straw ratio for an hour in a bomb digester with the variation of temperature from 80˚C to 120˚C and the active alkali (AA) concentration was increased up to 20%. At the temperature of 120˚C and with an AA charge of 20%, the screening process yielded a minimum pulp reject of 0.20%.However, the maximum pulp yield (55.16%) was achieved at the same temperature (120˚C) but reduced AA charge (16%) which are also the optimum pulping conditions for this study due to less chemicals (white liquor) and energy consumption. This optimum kraft pulping process can be used to convert more than half of the rice straw input into pulp with lower chemicals and energy use compared to the conventional wood-based pulping.

Keywords: Rice straw; Kraft pulping; Screened rejects; Active alkali charge; Pulp yield

1. Introduction

Rising population,improved literacy, enhanced communication, and industrialization in emerging nations were anticipated to boost the demand for paper and paperboards by 521million tons by 2021, and it is expected to be doubled by 2050(Kulkarni,2013; RISI, 2010; Juha-antti et al., 2012). The global production of pulp from wood fiber was quantified to be 158.19 million metric tons in 2021 and the projected growth is a CAGR of 2.7% by 2027 (Globe Newswire, 2022). Wood being the fundamental raw material in paper industry, it is likely that forthcoming paper industries will be facing raw material supply shortage due to severe declination of timber resources.

Particularly, Bangladesh is one of the most densely populated countries and has insufficient number of forests. Hence it has become vital to rely on alternative raw materials for continuous paper manufacturing. In Bangladesh, pulping (cooking raw material into pulp)of non-woody fibrous raw materials (jute, dhaincha, bananastem, corn stalks, sugar cane, bagasse, cotton stalks, okra plants, and straw) could be suitablea substitute of typical wood-based pulping

(Jahan etal., 2001; Covey et al., 2006). Approximately 2.5 billion tonnes of non-woody raw materials are accessible annually on a global scale; however, the majority of these commodities are currently untapped for pulp and paper production (Pandey, 1998). However, Bangladesh is abundantly occupied with rice straw , producing an annual amount of 34 million tons, accounting for almost 70% of entire residue (Jahan et al., 2006; ASB, 2008).

Interestingly, the composition of rice straw reveals that it has a comparatively less recalcitrance structure as it contains low lignin content (12-16%) along with suitable fiber length (1.41mm) (Waranyou, 2010). This structure is beneficial for maximum penetration of cooking chemicals by eliminating the need for a lengthy impregnation step and making the paper production more time efficient compared to wood-based pulping (Shao etal., 2017). Rice producing species also have shorter growth cycles and faster maturity than timber species and they produce higher pulp yields in less severe operating conditions. On the other hand, conventional karft wood pulping usually consists of a prolonged impregnation step, aiming for the opening up of the fiber vessels and ray channels at microscopic level, allowing much easier diffusion and movement of cooking chemicals. All of these scenarios indicate rice straw as a suitable raw material for making cellulose and paper sheets using the kraft pulping method.

Several studies investigated the rice straw pulp yield using kraft pulping. One study compared the screened yield of soda pulps obtained by short cycle pressure method and those by long cycle pressure (atmospheric) method (Fahmy and Ibrahim,1970). The study found short pressure cycle method resulted better yield values than long atmospheric method. Another study was investigated by (Yee et al., 2019) to evaluate the mechanical and physical properties of paper sheets made from pulping of rice straw with sodium hydroxide (NaOH) and chlorine dixide (ClO2). The study revealed an optimized temperature of 170˚C for 1 hour cooking time. However, optimization of operational parameters (temperature and alkali concentration) during conventional kraft pulping of rice straw has not yet been conducted.

Hence, the aim of this study is to investigate the 1) optimum temperature and 2) optimum active alkali (AA) concentration for achieving maximum pulp yield and minimum screened rejects during kraft pulping of rice straw. The viability of kraft pulping at lower temperatures for pulp yield and screened pulp rejects was explored to design an environmentally friendly, efficient, and non-wood pulping system.

2. Materials and Methods

The rice straw was collected from the district of Madaripur, Bangladesh. Long strands of rice straw were cut into 2-4 cm long pieces and were used as raw material in Kraft pulping process with white liquor as a media at three different temperatures from 80- 120˚C. The pulping temperature was optimized based on yield (%) and screened rejects (%) of the pulp prepared.

Dry content determination

Sized rice straw samples were taken in three separate containers and their weights (W1) were measured. After that, each container was dried at oven for 24 hours at 105˚C as per TAPPI standard. Subsequently, weights of oven-dried rice straw samples (W2) were measured. Finally, the dry content (%) and moisture content (%) were determined using equations (1) & (2).

$$Dry\ matter\ average\ (\%) = \frac{w2}{w1} \times 100$$
$$Moisture\ content\ average\ (\%) = 100 - Dry\ matter$$

White liquor preparation

To prepare the chemical solution (white liquor), the amounts of sodium hydroxide, sodium sulfide and water for the desired concentrations (16%, 18% and 20%) were calculated and 3 L liquor solution were prepared. The sulfidity level (S^{2-}) for each liquor was kept fixed at 25%. Then, the solutions were stirred in a magnetic stirrer to aid uniform mixing of solution.

Cooking

Sized rice straw samples were submerged in white liquor maintaining liquor to straw ratio of 15:1 in the bomb digester reactors with the capacity 5 L each for cooking. Cooking temperatures were varied from 80 to 120˚C while,- AA concentrations were varied from 16 to 20%. The cooking was conducted for 60 minutes. The cooking experiments conducted at different temperatures (80 – 100 ˚C) and varied AA percentages(16 – 20%) are shown in Table 1, 2, and 3.

Table 1: Cooking trials of kraft pulping at varied AA charge at 80˚C

Experiment	Experimental run	Raw RS (g) (dry basis)	Temperature (˚C)	Percentage of AA (%)	Sulfidity (%)
K-1	K-11	150	80	16	25
	K-12		80	16	25
	K-13		80	18	25
	K-14		80	18	25
	K-15		80	20	25
	K-16		80	20	25

Table 2: Cooking trials of kraft pulping at varied AA charge at 100˚C

Experiment	Experimental run	Raw RS (g) (dry basis)	Temperature (˚C)	Percentage of AA (%)	Sulfidity (%)
K-2	K-21	150	100	16	25
	K-22		100	16	25
	K-23		100	18	25
	K-24		100	18	25
	K-25		100	20	25
	K-26		100	20	25

Table 3: Cooking trials of kraft pulping under varied AA charge at 120˚C

Experiment	Experimental run	Raw RS (g) (dry basis)	Temperature (˚C)	Percentage of AA (%)	Sulfidity (%)
K-3	K-31	150	120	16	25
	K-32		120	16	25
	K-33		120	18	25
	K-34		120	18	25
	K-35		120	20	25
	K-36		120	20	25

Washing

After cooking, the black liquor was drained out from pulp. One digester's cooked pulped was thoroughly washed around 3-4 times using demineralized water to remove all residual substances such as excess chemicals, impurities etc. before screening and bleaching

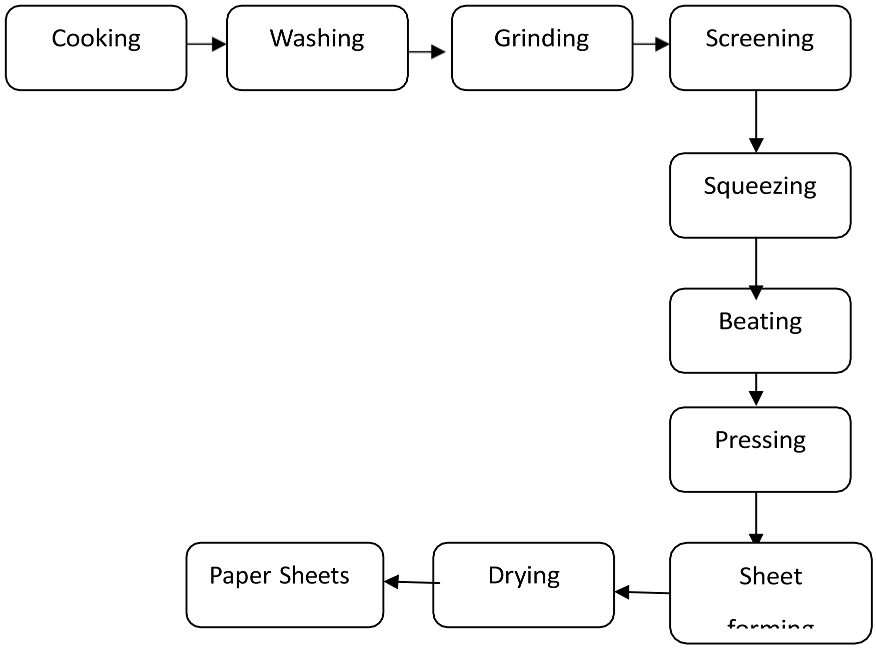

Figure 1: Block flow diagram of handmade paper sheets formation

Grinding and screening

The grinding process was carried out to remove extra lignin out from cooked pulp, via a grinding machine. Ultra-vibration screening was done at the screening machine to get a uniform pulp mixture. Besides that, undigested raw materials (rejects) were collected in the screen. The weights of the collected screened rejects (W3) were measured. Screened rejects were calculated using equation1.3 and the pulp was collected for yield calculation.

$$Screened\ Rejects\ (\%) = \frac{w3}{w2} \times 100$$

The yield of pulp was determined by the ratio of oven dried pulp (W3) to that of raw rice straw samples (W2) (equation 4).

$$Yield\ (\%) = \frac{w3}{w2} \times 100$$

Squeezing and dewatering

After feeding the pulp into the screw press machine, the screw conveyed it towards the bottom while squeezed water out through the screen and the dewatered pulp was discharged at the end of the screw press, resulting in the separation of water and solid pulp.

Paper making

Among several mechanical treatments a laboratory beater equipped with two knives was utilized first for making good consistency paper from pulp produced in preceding steps. The paper making procedure was performed according to TAPPI Standard. The handmade paper sheets were prepared through beating the pulp at the optimum hydrothermal treatment temperature as per TAPPI standard method (TAPPI T 205 sp- 02) using a laboratory hand-sheet former cylinder mold press. The wet pulp sheet (i.e. paper sheet before drying) was cushioned with blotter paper on one side and was sandwiched between two stainless circular steel plate for molding the wet paper sheet and squeezing out the extraneous water for a period of 24 hour.The wet sheet was then air dried to get smooth paper sheets.

3. Results and Discussion

Rice straw characterization

Rice straws were characterized by the dry matter and moisture content . Table 4 shows that the average values for dry matter and moisture content were 87.43% and 12.57% respectively which is slightly higher than the moisture content (11.69%) reported by a previous study (Biswas et al., 2017).

Table 4: Dry matter and Moisture content of rice straw

Sample ID	Weight of raw rice straw sample (gm)	Weight of Oven Dried sample (gm)	Dry matter (%)	Moisture content (%)	Dry matter Average (%)	Moistur e Average (%)
1	13.6	11.86	87.2	12.8	87.43% ± 0.20	12.57% ± 0.20
2	14.57	12.75	87.5	12.5		
3	16.46	14.42	87.6	12.4		

Optimization of temperature

Three pulping temperatures such as 80˚C, 100˚C and120˚C were investigated in this study which are comparatively lower temperature with respect to wood pulping temperature. Less recalcitrance structure and a relatively lower proportion of lignin content in rice straw allow the successful cooking with a faster rate at those lower pulping temperature. Effect of temperature variation on pulp yield (%) at each AA concentration (16%, 18% and 20%) is shown in Figure 2. The gradual increase in yield might be explained by the initiation of bulk-delignification phase. Usually, high rate of alkaline hydrolysis and peeling reactions (unwanted side reactions) cause severe carbohydrates loss which subsequently results a lower pulp yield (Wigell et al., 2007). (Johansson et al. 1984) demonstrated that around 140˚C, an increase in temperature affects the alkaline hydrolysis rate more than the delignification rate, resulting a lower yield.

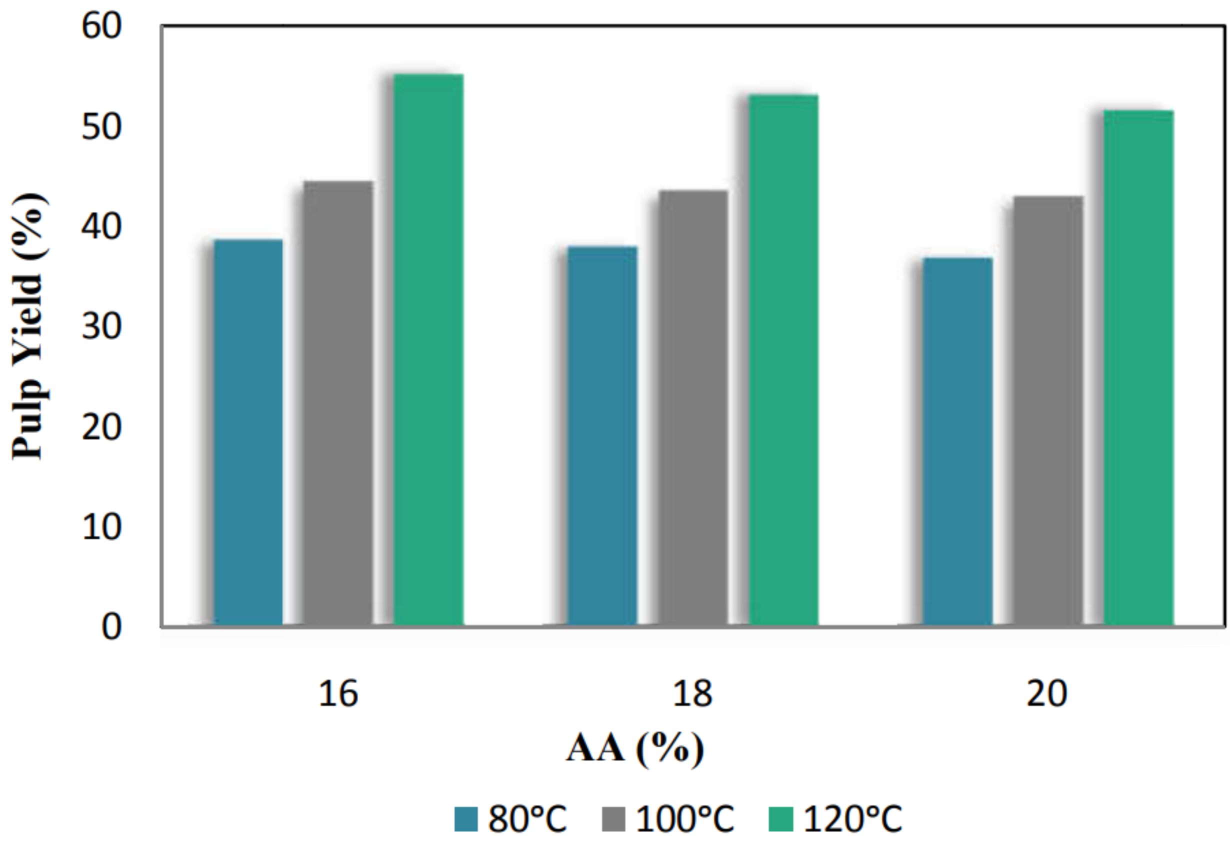

Figure 2: Impact of temperature on yield (%) at 16%, 18% and 20% AA concentration

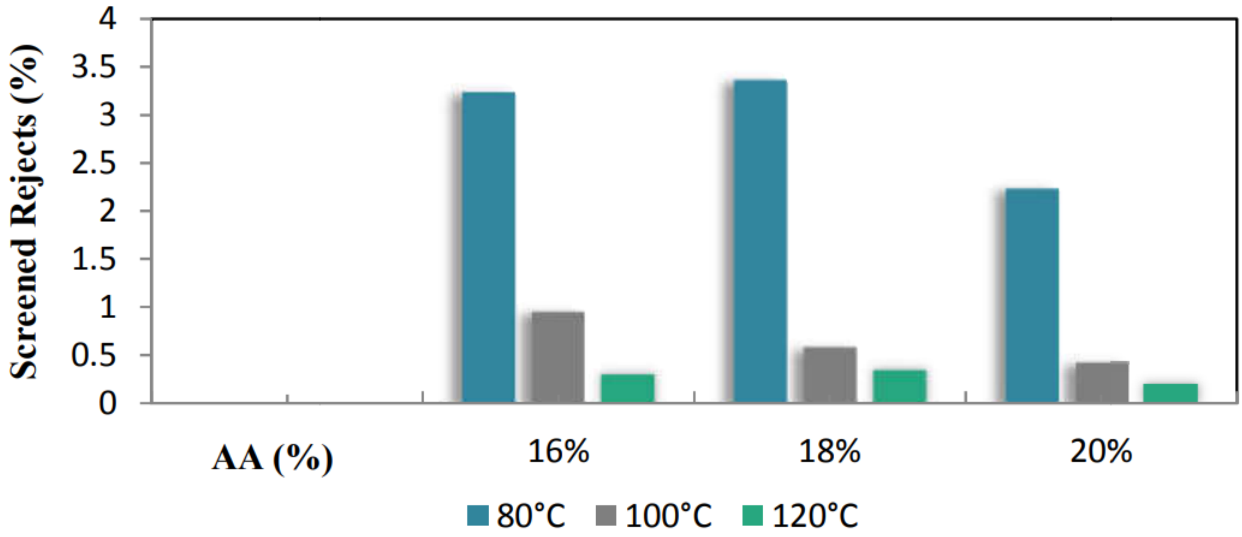

Figure 3: Impact of temperature on screened rejects (%) minimization

In case of screened rejects, opposite pattern for each fixed concentration is seen. Figure 3 shows that escalation of temperature led to a sharp declination of screened rejects . When temperature was increased from 80˚C to 100˚C, screened rejects were minimized almost 70.37% at 16% AA concentration. Further elevation above 100˚C exhibited in marginal reduction of screened rejects.The lowest screening rejects (%) was 0.195% obtained at 120˚C for 20% AA. This might be explained by the longer retention of initial delignification stage at low temperature (80˚C) when only hemicelluloses de-acetylation and physical dissolution reactions are predominant. However, as the temperature increases, the reactions shift at favorable kinetics for delignification of rice straw. At 120˚C, temperature boosts the random cleavages of both phenolic and non-phenolic (β-O-4) lignin bonds. Consequently, rejects gets dropped to a value of 0 195% at 120˚C for 20% AA concentration. As a result, for the minimization of rejects (%) and increase the attainment of yield (%), 120˚C can be considered as optimum temperature for kraft pulping.

Optimization of Active Alkali concentration

Effects of AA charge on pulp yield and screen rejects was investigated in this section. Figure 4 illustrates the negative impact of AA on pulp yield .The Figure 3 depicts that a 2% rise of AA charge (16%to 18%) led to a total pulp yield loss of 3.71% at 120˚C. Similarly, the maximum pulp yield reduction of 5.10% occurred for increasingAA charge from 18% to 20% at 80˚C. Therefore, it is quite apparent that, rise of alkali concentration had a moderate influence in yield loss. Such yield loss due to rise of alkali concentration might be explained by severe attack of OH- ions on the terminals of long cellulose chains. According to a study (Brännvall, 2017), peeling of carbohydrate chain polymers in high alkali media is fundamentally responsible for continuous reduction of the terminal sugar of polymer chain.

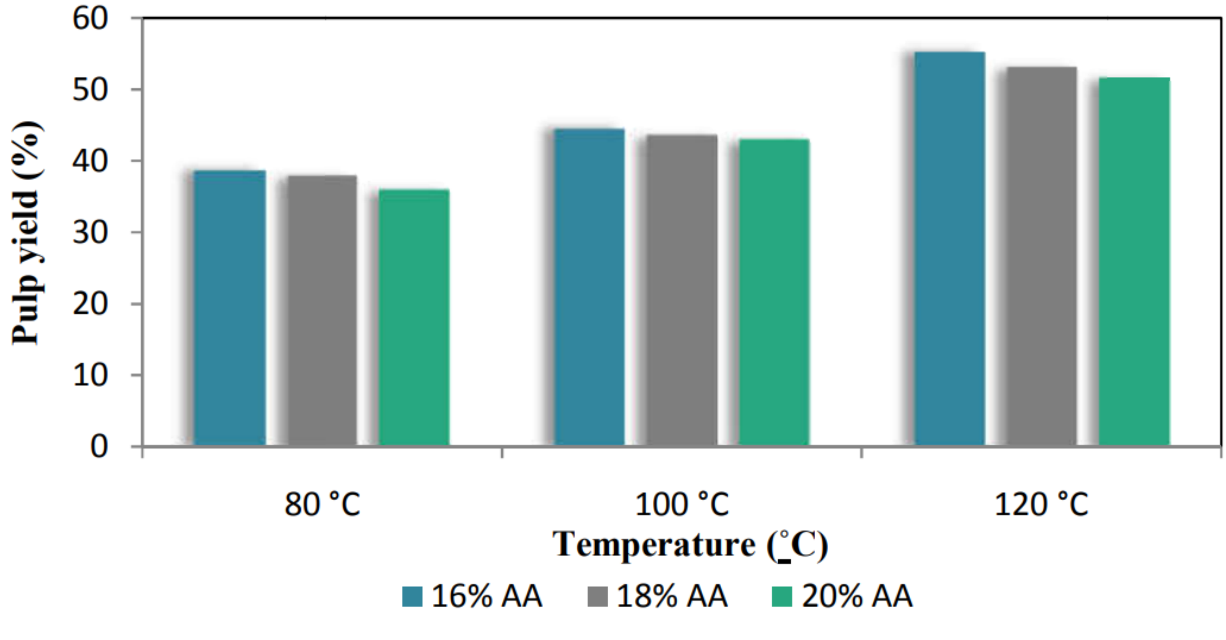

Figure 4: Impact of AA on yield (%) values at varied temperatures

The terminal sugar gets reduced by the alkali ion and peeled off from the chain, subsequently converting into an isosaccharinic acid in the solution. The new terminal becomes prone to another attack and the peeling continues leading to gradual losses of yield values. The highest value of yield was 55.16% at 16% AA at 120 ˚C.

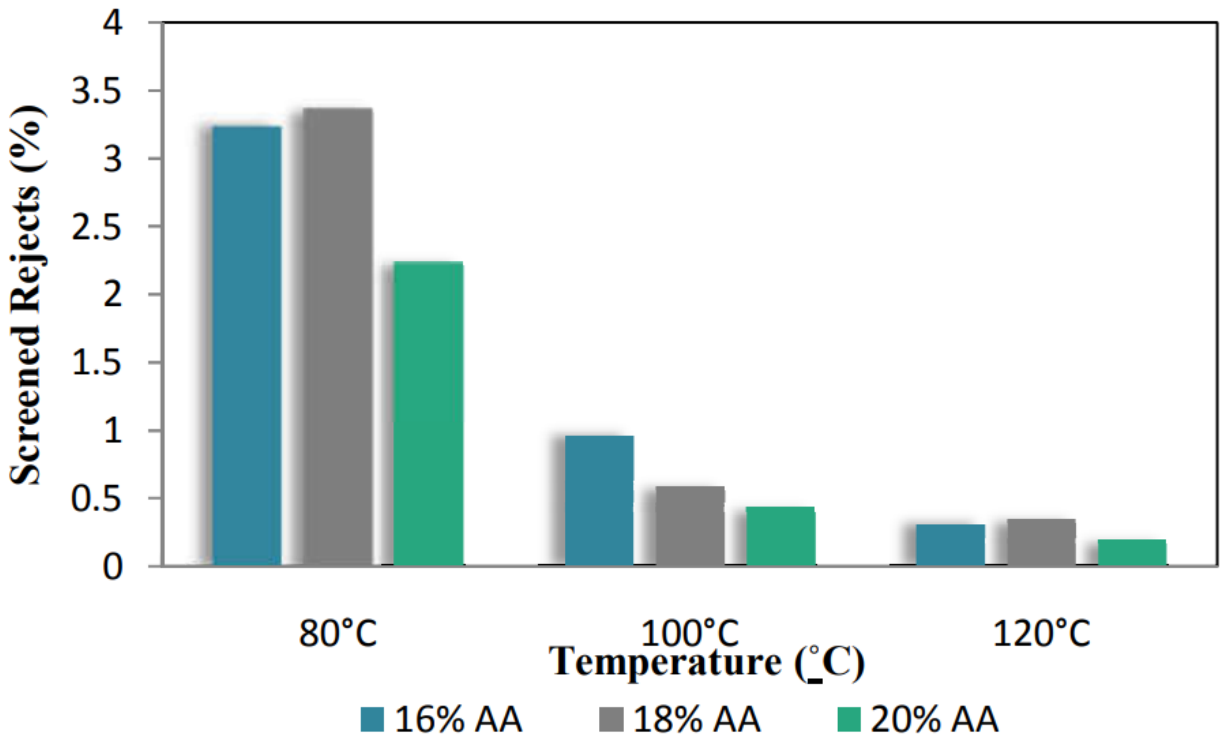

Figure 5: Impact of AA on screened rejects at different temperatures

In case of screened rejects, the rise of alkali concentration is shown in Figure 5. At 80°C, the screen reje ts were minimized by 30.86% when the AA charge was increased from 16 to 20% although above 100°C the variations in AA concentrations had minimal impact in minimizing screened rejects. Gautam et al. (2016) and Bhardwaj et al. (2005) both observed a similar reduction in screened rejects in strong alkali environment in soda pulping of rice straw and E. binata respectively. The rate of hydrolysis of the xylan molecule is much faster compared to hydrolysis of cellulose or glucomannan (Nieminen et al. 2014) for which amount of rejects get declined. This is because such high alkali charge not only promotes severe loss of carbohydrates but also escalates the rate of bulk delignification.

4. Conclusions

This study investigates optimum temperature and AA concentration for obtaining enhanced yield and minimized screened rejects during kraft pulping of rice straw. The experimental data illustrates that the highest 55.16% pulp yield was obtained at 120°C and 16% AA. However, minimum yield values (38.68% at 16% AA, 37.99% at 18% AA, and 36.05% at 20% AA) and maximum non-digested rejects were recorded at 80°C pulping temperature. Thus, it can be concluded that such a low temperature does not economical to conduct kraft pulping. Additionally, moderate yield losses were observed at higher alkali media. The major pulp yield reduction of 5.10% occurred at increasing AA charge from 18% to 20% at 80°C. This implies that120°C temperature and 16% AA charge are the optimal cooking operating conditions for attaining the highest yield and to minimize screening rejects.

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