CELLULOSE CHEMISTRY AND TECHNOLOGY

OPTIMIZING SODA-MONOETHANOLAMINE PULPING: IMPACT ON CELLULOSE DEGRADATION, RHEOLOGY AND PULP QUALITY

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Received July 1, 2025

This study investigated the use of monoethanolamine (MEA) as an additive in soda pulping to decrease alkali consumption, improve pulping efficiency, and reduce cellulose degradation. MEA was added at various concentrations. Results show that higher MEA concentrations improved delignification, preserved cellulose, and significantly reduced pulp rejects. A higher MEA addition resulted in pulp with a lower kappa number, fewer rejects, and higher yields compared to the control. MEA proved to be an effective alkali additive in the pulping process, providing equivalent pulp yield and kappa number to a control soda pulp with reduced alkali and different combinations of MEA. Rheological studies showed that higher alkali charges with MEA promoted effective delignification, but also caused cellulose degradation, reflected by lower pulp viscosity. Conversely, lower alkali charges with MEA showed minimal changes in kappa number, but led to a significant increase in pulp viscosity and a reduction in cellulose degradation.

Keywords: monoethanolamine, Organsolv pulping, soda pulping, cellulose degradation

INTRODUCTION

The pulp and paper sector, a cornerstone of global manufacturing, is increasingly focused on sustainability, resource efficiency, and minimizing the release of environmentally hazardous chemicals during the pulping and bleaching processes. The traditional reliance on wood as a key raw material faces challenges due to environmental concerns, deforestation, and the growing need to reduce carbon emissions. These issues have prompted research into alternative raw materials and innovative techniques that may meet the rising demand for paper while lessening environmental impacts. While planting fast-growing species could ease the shortage of forest resources, attention is shifting towards non-wood fibers,[1-3] such as sugarcane bagasse, a by-product of the sugar industry.

Sugarcane bagasse presents a viable alternative due to its abundance, renewable nature, and cost-effectiveness. India ranks among the world's leading producers of sugarcane and sugar. Over the past 60 years, the Indian sugar sector has expanded rapidly and without significant issues; consequently, the area dedicated to sugarcane cultivation and sugar production has been steadily increasing. India currently trails Brazil in both sugarcane production (303.83 million tons) and cultivated area (5.11 million hectares).[4] Sugarcane bagasse constitutes a substantial portion of the waste generated by the sugar industry and is also among the world's largest agricultural residues.[5,6] This residue is produced in significant quantities; for every ton of sugarcane, about 280 kg of wet bagasse is generated.[7] However, large-scale adoption of bagasse requires overcoming considerable technical challenges, particularly in pulping and processing, to achieve quality standards comparable to those of wood-based paper. The primary issue with bagasse pulping is the high pith ratio of the stalks, which makes up about 30% of the total weight of the stalk.[3] Bagasse is utilized for four main paper categories: packaging and boxes; writing, printing, and photocopier paper; tissues; and newsprint.[8]

Conventional soda and soda-anthraquinone pulping are currently the most widely used methods for processing non-wood fibers. The high silica content in non-wood raw materials poses a significant challenge for black liquor recovery, even with these well-established methods. Silicates

Cellulose Chem. Technol., ***60*** *(1-2), 117-127 (2026)*

create serious issues in liquor evaporation, combustion, and the lime kiln, considerably reducing the efficiency of the alkali recovery rate.[9,10] Recent studies have investigated converting black liquor components into value-added products, such as high-purity lignin, furfural, and acetic acid, as more sustainable alternatives to burning.[11-13] Furthermore, the silica issues associated with soda pulping of non-wood fibers can be mitigated by adopting organosolv pulping methods that utilize organic solvents. To address these challenges, numerous organosolv pulping processes have been examined. The range of organosolv systems evaluated is extensive, as any organic solvent capable of dissolving lignin-type compounds can be considered a viable option.[14] Additionally, organosolv methods often employ organic compounds with relatively low molecular weights as delignification agents.[15] The investigation of quantitative fractionation, or the breakdown of the constituent parts of plant tissue, is a crucial aspect of all organosolv processes. This part of the process should preserve the material as much as possible, allowing it to be utilized in subsequent phases of transformation and revalorization.[16] However, only a limited number of organosolv methods demonstrate high efficiency and selectivity.

Monoethanolamine (MEA) is used as one of the organic solvents in organosolv pulping, alongside other alkanol amines. Previous studies have shown that MEA provides highly selective delignification of annual plants.[9] The use of alkanolamines, including mono-, di-, tri-ethanolamines, and related compounds for the pulping of lignocellulosic materials began in the 1930s. These solvents were utilized in either pure form or in mixtures of different alkanolamines in pulping processes. These compounds were examined as potential pulping chemicals or additives in conventional pulping methods such as kraft, soda, or sulfite, offering notable advantages, including chemical recoverability and environmental benefits.[17-21] Hergert (1998) provided a comprehensive review of the literature on organosolv pulping research.[11] In several studies focused on using MEA for pulp production, MEA was primarily applied to wood as the main raw material and was only used in alkaline pulping to assist the delignification process.[22-24] The findings indicate that MEA's ability to dissolve lignin is limited when wood is used as the pulping raw material, particularly for softwoods, where high temperatures are required to produce bleachable pulp grades with low kappa numbers. MEA undergoes significant decomposition at these temperatures, resulting in dark and challenging-to-bleach pulps.[25] MEA is used in various industrial applications, including gas sweetening, textile processing, metalworking, surfactants, and specialty cleaner formulations, underscoring its versatility.[26] However, MEA use requires caution; exposure poses significant health risks, primarily due to its corrosive and irritant properties.[27] It also poses hazards to aquatic life upon entering water bodies, and it persists in the environment because of its slow degradation. Utilizing recycled MEA can be cost-effective and promote a circular economy, minimizing waste and reusing resources, potentially reducing production costs.[28]

Numerous researchers have also explored MEA alone for pulping of non-wood fibers.[29-31] Jahan and Farouqui,[32] and Jahan *et al.*[33] explored the soda MEA pulping of jute at fixed conditions. Chibudike *et al.*[21] focused on pulping of sugarcane bagasse under MEA-only systems. However, such research has largely focused on pulp yield and kappa number, without investigating the underlying cellulose degradation or the rheological behavior of pulp. Additionally, the interaction between alkali and MEA dosages and their effects on delignification and pulp characteristics has not been examined for sugarcane bagasse. This study addresses these gaps by evaluating the effect of MEA as a pulping additive in the soda pulping process of depithed sugarcane bagasse, with a focus on cellulose degradation, pulp rheology, and the optimization of MEA-alkali combinations.

EXPERIMENTAL

Raw materials

The depithed sugarcane bagasse used in this research was procured from the Century Pulp and Paper Mill, Lalkaun, Nainital, Uttarakhand, India. Upon receipt, the bagasse was shredded and dried to about 90% dryness through air drying at room temperature and stored in polyethylene bags for further use.

Raw material characterization

The raw material was prepared according to the Technical Association of the Pulp and Paper Industry (TAPPI) standard method T 257 om-02 for preliminary chemical analysis before chemical characterization and pulping.[34] Depithed bagasse was milled into powder in a laboratory Wiley mill (A. Gallenkamp & Co Ltd., London), and the fraction passing through a 40 mesh sieve but retained on a 60 mesh sieve was selected for analysis of moisture content (T 264 cm-97),[35] water solubility (T207 cm-99),[36] 1% sodium hydroxide solubility (T212 om-02),[37] alcohol-benzene solubility (T204 om-88),[38] holocellulose (useful method T 249),[39] alpha cellulose (T 203 cm-02),[40] lignin (T222 om-02),[41] and ash (T211 om-02).[42]

Pulping experiments

To determine the Soda pulping conditions, preliminary experiments were conducted varying the liquor to bagasse ratio (L:B), alkali charge, and h-factor. The L:B was varied between 6:1 and 7:1 (for bagasse pulping in laboratory digesters the liquor-to-bagasse ratio must be relatively high due to the low-bulk density of bagasse and higher liquor absorption). The alkali charge was tested at 10% to 18% NaOH, and the h-factor was tested at 1200 and 1400 with a maximum temperature of 170 °C retained for 60 min to 75 min, respectively. All pulping experiments were conducted in an electrically heated rotating digester (Universal Engineering Corporation, India), equipped with six stainless steel autoclaves of 2.5 L capacity, each rotating in a heated ethylene glycol bath. For each experiment, 100 g of bagasse per batch was used. The percentage data pulp yields, chemicals, additives, *etc.*, are given in the context of the pulping experiment based on oven-dry (O.D.) bagasse. Soda pulping of (control) bagasse was carried out at a 7:1 (L:B) ratio, with a 12% alkali charge at 170 °C for 60 min. The time taken to reach the maximum temperature from the room temperature was 150 min. The H-factor of 1200 was maintained during the pulping. The conditions for soda pulping were determined based on total pulp yield, screened pulp yield, pulp rejects, and kappa number as follows, and were used as the standard for all subsequent pulping experiments. The experimental matrix and pulping conditions used in this study are summarized in Table 1.

Table 1
Experimental matrix and operating conditions for soda-MEA pulping of depithed sugarcane bagasse

Experiment set	Alkali charge (%)	MEA charge (%)	L:B ratio	H-factor
Control	12	0	7:1	1200
Soda–MEA	12	10–60	7:1	1200
Soda–MEA (varying alkali–MEA charge)	9–12	10, 20, 30	7:1	1200

Soda-MEA pulping

MEA was added as a pulping additive to the pulping liquor under soda pulping at different concentration ranges of 10% to 60% to investigate its effect on pulping properties and delignification in comparison to the control without MEA additive. MEA was added directly into the pulping liquor before pulping.

Soda-MEA pulping with varying alkali charge and varying MEA concentrations

Based on the result for varying MEA concentrations at constant alkali charge, an experimental design was implemented to investigate the combined effects of MEA and alkali concentration. MEA was varied at three levels (10%, 20%, and 30%), and alkali was varied at four levels (9%, 10%, 11%, and 12%). All experiments were performed under constant conditions of 170 °C maximum temperature, 60 minutes at maximum temperature, and an L:B ratio of 7:1. This matrix allowed the assessment of how MEA dosage influences performance at different concentrations of alkali, offering insights into the possibility of substituting alkali with MEA.

Pulp evaluation

After cooking, the bagasse pulps were thoroughly washed with warm water (40-50 °C) using a fine muslin cloth to remove the residual black liquor. The cleaned pulp was then disintegrated in a laboratory-scale disintegrator. The disintegrated pulps were screened with a vibratory flat screen (Lorentzen & Wettre, Canada) with a slot size of 0.15 mm at approximately 0.5% consistency to determine the screened pulp yield. The rejects remaining on the screen after the screening of the pulp slurry were collected and oven-dried to determine pulp rejects. The screen accepts were collected on a fine muslin cloth to retain maximum fines, after which it was dewatered and stored in polyethylene bags at 4 °C for further analysis and processing. The kappa numbers of all pulp samples were determined according to T 236 cm-85[43] to evaluate the extent of delignification achieved under different pulping conditions, lignin and cellulose content in pulp were also determined.

Rheometric analysis

The rheological tests were conducted using a RheolabQC rotational rheometer, equipped with a thermal bath to maintain a controlled temperature. Test samples of bagasse pulp were dissolved in a CED solution at a concentration of 5% and then placed in the viscometer, which operated at 25 °C ± 0.1 °C, using the coaxial cylinder geometry (CC27) with a 0 mm gap. The outer cylinder remains stationary, and the inner cylinder is rotated as a function of the applied shear rate. Flow curves were carried out in controlled shear rate mode from 0 to 100 s^{-1} in 120 s.

RESULTS AND DISCUSSION

Chemical composition of sugarcane bagasse

The purpose of this section is to provide basic information concerning the chemical components of bagasse. The chemical components play an important role in determining how the material will perform in the end products as well as in their production. The solubility of bagasse in both cold and hot water was measured at 2.36±0.01% and 4.41±0.06%, respectively. The 1% NaOH solubility for bagasse was 27.73±0.2%, which is lower than what Agnihotri *et al.* reported.[44] The NaOH solubility indicates the extent of fungal decay or degradation that can occur due to factors like heat, light, oxidation, *etc*. NaOH solubility increases when the biomass decays or degrades. Additionally, it also reflects the breakdown of cellulosic substrates during the bleaching and pulping processes. The alcohol-benzene solubility of the raw material, which helps identify the presence of wax, tannins, resins, *etc*., was found to be 2.77±0.03% for bagasse. This aligns closely with findings from Chambon *et al.*[45] The ash content was measured at 1.85±0.02%, which is consistent with the data reported by Rainey and Covey.[8] However, it is lower in comparison to most non-woody biomasses.[46] A higher ash content can indicate a greater presence of inorganic materials, which may pose challenges for chemical recovery. The lignin content in bagasse was found to be 22.4±0.5%. A lower lignin content is advantageous as it translates to reduced chemical requirements during both the pulping and bleaching stages. Furthermore, the holocellulose and alpha-cellulose contents in bagasse were 72.16±0.5% and 41.78±0.45%, respectively. A high cellulose content is a positive sign, confirming that this biomass is well-suited for applications in pulping and papermaking.

Effect of soda-MEA pulping with varying MEA charge

Soda-MEA pulping was conducted using varying concentrations of MEA additive, ranging from 10% to 60%, under controlled soda pulping conditions: 12% NaOH, H-factor 1200, maximum temperature 170 °C for 60 min, and a 7:1 (L:B) ratio. During the soda pulping process, an increase in MEA charge significantly influenced the total pulp yield, screened pulp yield, pulp rejects, kappa number, and cellulose content in pulp (Fig. 1). Under the control condition without MEA, the total pulp yield was 58.01±1.4%, the screened pulp yield was 56.34±1.35%, pulp reject was 1.67±0.09%, kappa number of 37.53±1.83, and cellulose content was 88.22±1.21. The total pulp yield 58.01±1.4% for control without MEA decreased to 57.71±1.3% with the addition of 10% MEA, whereas the screened pulp yield increased from 56.34±1.35% to 57.22±1.29%, the pulp rejects decreased significantly from 1.67±0.09% to 0.49±0.08%, kappa number decreased from 37.53±1.83 to 27.47±2.35 and cellulose content increased from 88.22±1.21 to 90.93±1.19. The addition of 10% MEA showed improvement in pulping efficiency. Further increasing the MEA addition from 20% to 60% resulted in a decrease in total pulp yield from 56.52±1.1% to 54.17±1.2%, a decrease in screened pulp yield from 56.10±1.09% to 54.01±1.17%, and pulp rejects from 0.42±0.02% to 0.16±0.03% (Fig. 1a, b). Kappa number decreased significantly from 27.47±2.35 to 15.57±1.61 with the addition of 10% to 30% MEA, although on subsequent MEA increases from 40% to 60% there was minimal change in kappa number decreasing from 13.66±1.71 to 11.75±1.15 (Fig. 1c). Cellulose content increased significantly from 88.22±1.21 to 93.86±1.17 with the addition of 10% to 30% MEA, although on subsequent MEA increases from 40% to 60% there was minimal change in cellulose content from 94.33±1.51 to 94.79±1.13 (Fig. 1d). The results showed that with the addition of MEA at 10% charge the pulping efficiency improved, and on further increase of MEA addition up to 30% charge changes were observed in total pulp yield, screened pulp yield, pulp rejects, kappa number, and cellulose content in pulp, but on further increase in MEA charge from 40% to 60% there were no significant changes (Fig. 1). The optimal results were achieved at a 30% MEA charge, total pulp yield of 55.76±1.5%, with a screened pulp yield of 55.42±1.23%, pulp rejects of 0.34±0.04%, kappa number of 15.57±1.61, and cellulose content of 93.86±1.17%. A 30% charge in soda-MEA pulping was sufficient to ensure nearly complete removal of non-cellulosic materials. Therefore, any further increase in MEA charge beyond this threshold was unnecessary for bagasse pulping.

The results show that the addition of MEA as an additive effectively enhances the delignification process in soda pulping, as indicated by the decreasing kappa number with increasing MEA charge. The consistent decline in pulp rejects with rising MEA content suggests improved pulp process efficiency. The cellulose content in pulp increases with the rising charge of MEA (Fig. 1d), indicating that MEA specifically targets lignin while preserving cellulose content, and proved to function as an antioxidant and to prevent oxidative degradation of polysaccharides.

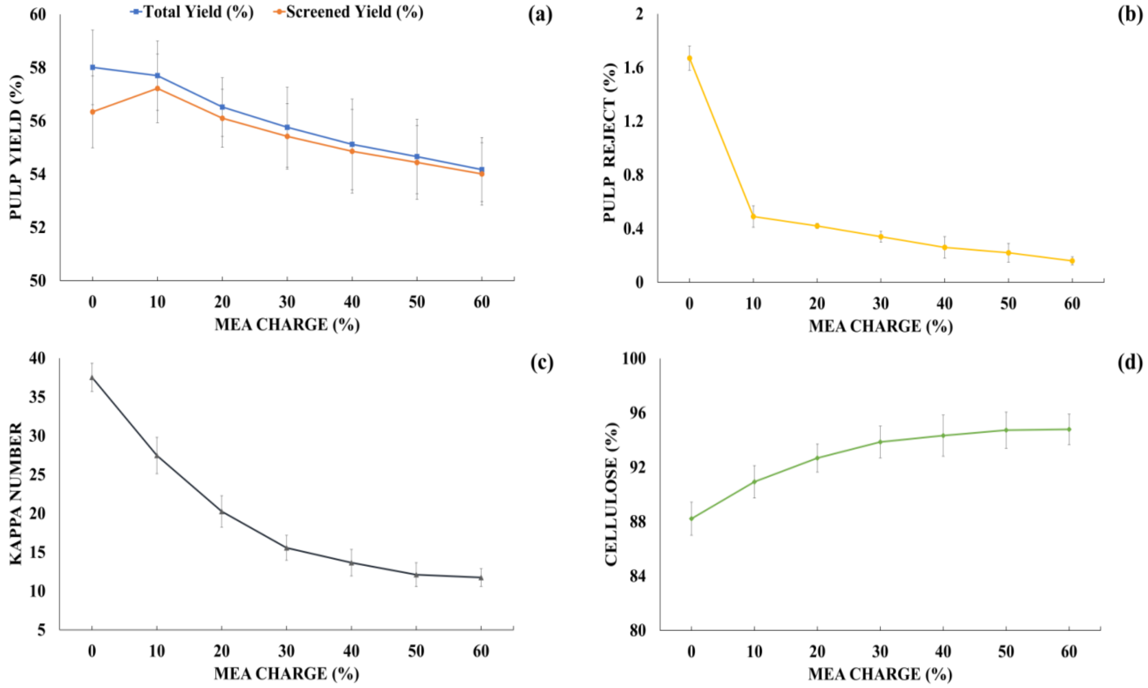

Figure 1: Pulping properties of bagasse with MEA: (a) Pulp yield, (b) Pulp rejects (c) Kappa number, (d) Cellulose content in pulp

Effect of soda-MEA pulping with varying alkali and MEA charge

During soda-MEA pulping of sugarcane bagasse, it was observed that, with the addition of MEA additive, there was an initial increase in screened pulp yield compared to the control without MEA addition, the cellulose percentage in pulp increased with the addition of MEA additive. The pulp rejects and kappa number decreased significantly up to the addition of 30% MEA; however, after further addition of MEA, there was not much decrease showing not much change. The addition of varying MEA additive charges from 10% to 30% with varying alkali charges from 9% to 12% was taken for further studies. The distinctive variations in total pulp yield, screened pulp yield, pulp rejects, kappa number, and cellulose content in pulp were determined as resulting from varying the alkali and MEA charge.

Impact on pulp yield, screen pulp yield, and pulp rejects

With the increase in MEA additive and alkali charge, there was a decrease in total pulp yield; however, there was not much difference in the screened pulp yield. At a 9% alkali charge with a 10% MEA charge, the total pulp yield was 60.87±2.4%, while the screened pulp yield was 56.83±2.24%. Conversely, at a 12% alkali charge with a 30% MEA charge, the total pulp yield dropped to 55.76±1.5%, whereas the screened pulp yield was 55.42±1.23%. As the concentration of MEA additive and alkali charge increased, there was a reduction in pulp rejects, resulting in a higher value for the screened pulp yield. The pulp rejects peaked at 4.04±0.16% at a 9% alkali charge with a 10% MEA charge; however, they were minimized to 0.32±0.04% at a 12% alkali charge with a 30% MEA charge (Fig. 2).

At a 9% alkali charge with a 10% MEA, the total pulp yield was 60.87±2.4%, the screened pulp yield was 56.83±2.24%, pulp reject was 4.04±0.16%, and the kappa number was high at 55.80±2.23, indicating poor delignification of bagasse and less effective pulping. At a 9% alkali with 20% and 30% MEA additive, both total pulp yield and screened pulp yield decreased to 58.88±2.0% and 58.28±1.7%, and 57.45±1.95% and 57.09±1.67%, respectively (Fig. 2a, b). 9% Alkali with 30% MEA charge yielded better results than at 10% and 20% MEA. At a 9% alkali, there was a sharp decrease in pulp rejects from 4.04±0.16% for 10% MEA to 1.43±0.05% for 20% MEA, and thereafter with an increase in MEA additive to 30% there was not much decrease in pulp rejects, which recorded 1.19±0.03%.

At a 10% alkali charge with a 10% MEA charge, the total pulp yield was 59.14±1.4%, the screened pulp yield was 57.03±1.35%, pulp reject was 2.11±0.06%, and the kappa number was high at 43.42±1.83, indicating poor delignification of bagasse and less effective pulping. At a 10% alkali with 20% and 30% MEA charge, both total pulp yield and screened pulp yield decreased to 57.87±1.8% and 56.95±1.7%, and 57.13±1.78% and 56.34±1.68%, respectively. The screened pulp output was marginally higher at 20% MEA compared to the 10% MEA, indicating improved pulp yield. At a 10% alkali there was sharp decrease in pulp rejects from 2.11±0.06% for 10% MEA to 0.74±0.04% for 20% MEA, and thereafter with an increase in MEA additive to 30%, there was not much decrease in pulp rejects, which was 0.61±0.02%.

At an 11% alkali charge with a 10% to 30% MEA charge, the change in total pulp yield was 57.62±1.9% to 56.76±1.2%, the screened pulp yield was 56.82±1.82% to 56.42±1.15%, pulp reject was 0.80±0.03% to 0.34±0.06%. At a 12% alkali charge with a 10% to 30% MEA charge, the change in total pulp yield was 57.71±1.3% to 55.76±1.5%, the screened pulp yield was 57.22±1.29% to 55.42±1.23%, pulp reject was 0.49±0.08% to 0.32±0.04%.

At a 9% and 10% alkali charge with 10% to 30% MEA additive, the screened pulp yield were nearly identical, but with significantly lower kappa number and pulp rejects. This suggests a more targeted delignification process, enhancing pulp quality. As the alkali charge increased to 11% or 12% and the MEA charge increased from 10% to 30%, both total pulp yield and screened pulp yield decreased and there was not much change in pulp rejects.

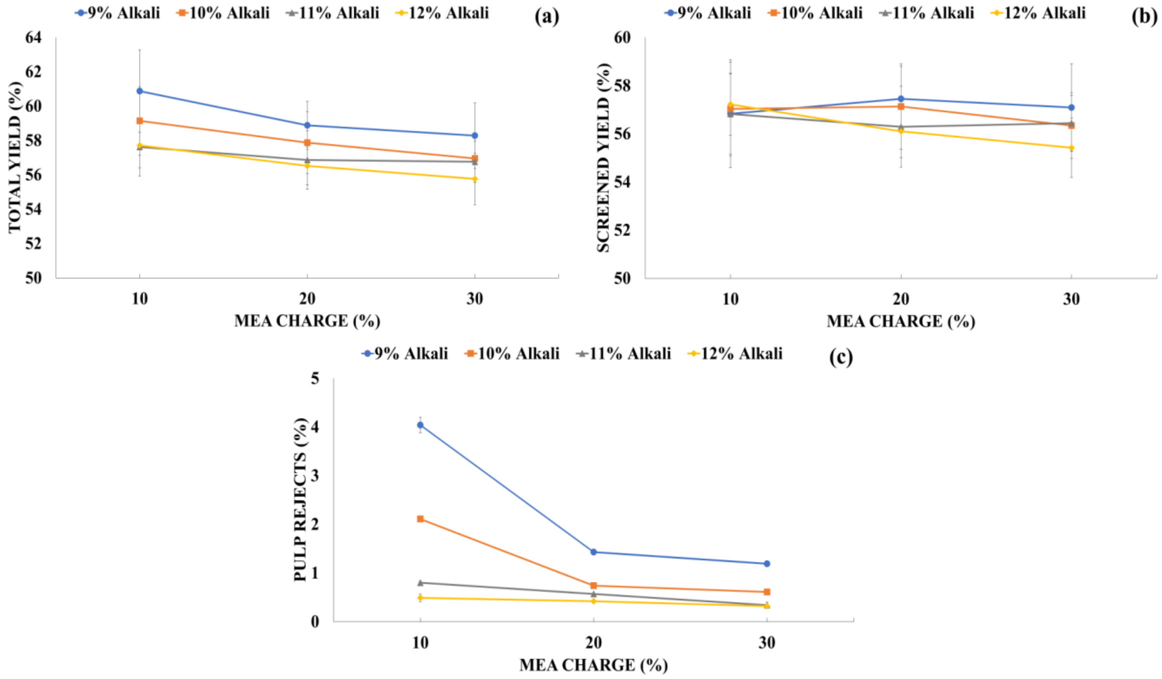

Figure 2: Pulping properties of bagasse with varying MEA and alkali charge: (a) Total pulp yield, (b) Screened pulp yield, (c) Pulp rejects

At lower 9% and 10% alkali charge, there was sharp decrease in pulp rejects with the addition of MEA additive from 10% to 20% and on further addition of 30% MEA there was not much change (Fig. 2c). The pulp rejects decreased when the MEA dose was increased from 10% to 30% across the whole alkali range: 9-12%. This indicates that MEA reduces pulp rejects below the control condition and contributes to more efficient pulping.

Impact on kappa number

To determine the level of residual lignin content or the bleachability of finished or in-process pulp, the kappa number of pulp is a key test method. It measures the completeness of the pulping process for many types of chemical, semi-chemical, and mechanical pulps, and is used to estimate the required amount of bleaching chemicals.

As the concentration of the MEA additive increased across various alkali levels, the kappa number decreased (Fig. 3). At a 9% alkali charge with a 10% MEA additive, the kappa number was 55.80±2.23, whereas at a 12% alkali charge and a 30% MEA charge, the kappa number decreased significantly to a minimum of 15.57±1.61. The MEA additive significantly influenced lignin removal, leading to a lower kappa number compared to the control as 37.53±1.83 for a 12% alkali charge without the MEA additive. When utilizing the MEA additive in soda pulping with varying alkali charges, the kappa numbers for 10% MEA at alkali concentrations of 9% and 10% were higher than for the control. The recorded values were 55.80±2.23 and 43.42±1.83, respectively, while for a 9% alkali charge with a 20% MEA charge, it was 40.33±2.18. With a 9% alkali charge and a 30% MEA additive, the kappa number fell below that of the control at 33.23±1.76, indicating a more effective pulping condition than 12% alkali alone. Likewise, at a 10% alkali charge with a 20% MEA additive, the kappa number was lower than the control at 31.61±20.07, representing another effective pulping alternative to the 12% alkali alone. Adding more MEA above a 10% charge with 11% and 12% alkali resulted in a significantly lower kappa number compared to the control with 12% alkali alone. The kappa number dramatically decreased at a 30% MEA charge, reaching 33.23±1.76 at a 9% alkali charge, 23.81±1.91 at a 10% alkali charge, 17.50±1.18 at an 11% alkali charge, and 15.57±1.61 at a 12% alkali charge.

Therefore, pulping processes that previously relied solely on higher alkali charges to achieve lower kappa numbers can be effectively replaced by optimal combinations of lower alkali charges with appropriate MEA additive charges, thereby reducing alkali consumption in the pulping process. This indicates that incorporating MEA into the soda pulping process significantly improves delignification efficiency. The most substantial improvement occurred at a 30% MEA charge with 11% and 12% alkali charges, resulting in superior delignification and a kappa number that was halved compared to the control condition without MEA.

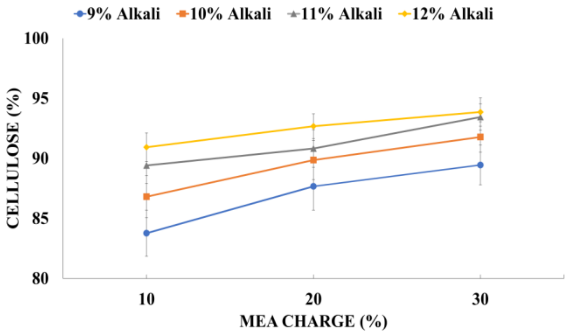

Figure 3: Kappa number of bagasse pulp with varying MEA and alkali charge

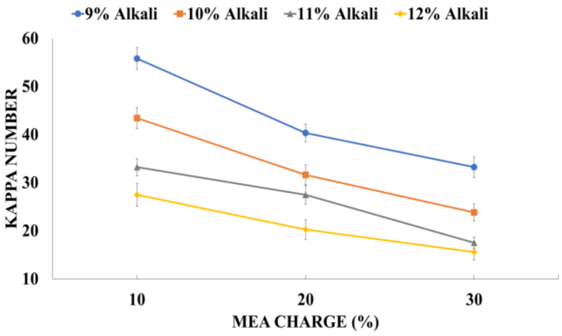

Figure 4: Cellulose content of bagasse pulp with varying MEA and alkali charge

Impact on cellulose in pulp

It was observed that as the alkali and MEA additive increased, there was not much change in the screened pulp yield; however, there was a significant increase in the cellulose content of the pulp (Fig. 4). At a 9% alkali charge coupled with a 10% MEA charge, the pulp's cellulose was lowest at 83.77±1.92%. With 20% and 30% MEA charges, the cellulose content in the pulp increased to 87.67±1.75% and 89.45±1.51%, respectively. The cellulose in the pulp rose significantly with the increased MEA concentration from 10% to 30% across all alkali ranges, suggesting that MEA specifically targets lignin while preserving cellulose materials. Compared to the control condition, the comparison indicates that adding MEA in the soda pulping boosts delignification, as evidenced by the lower kappa numbers and fewer pulp rejects in all circumstances. The inclusion of MEA, particularly at 30% across all alkali ranges, greatly improved the pulp quality, resulting in lower pulp rejects and kappa number, while increasing cellulose content in the pulp, even though the total and screened pulp yields remained similar to the control without the MEA additive.

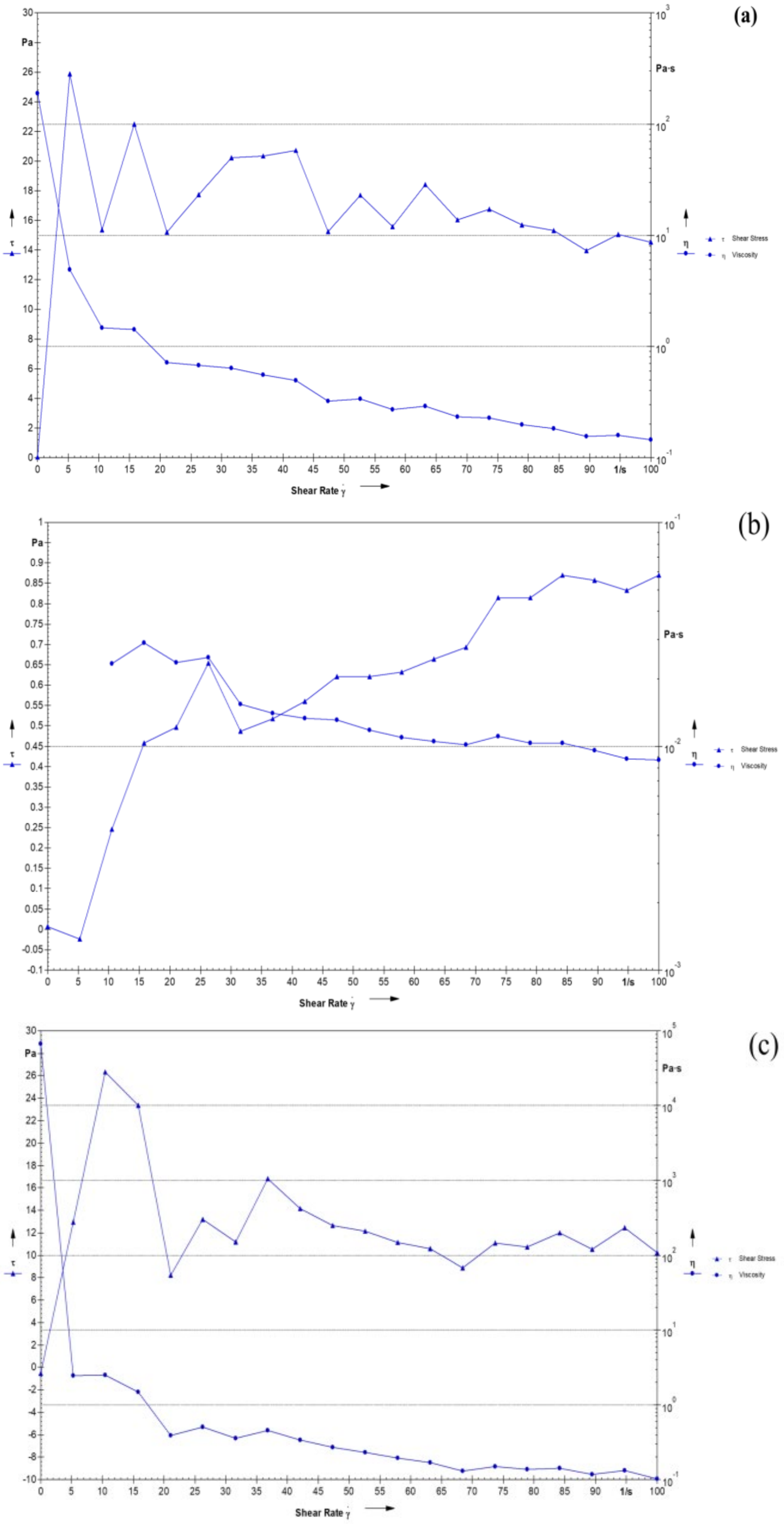

Figure 5: Viscosity of bagasse pulp: (a) 12% NaOH, (b) 12% NaOH with 30% MEA, (c) 9% NaOH with 30% MEA

Rheometric analysis of pulp with and without MEA additive

The rheological studies of the pulp with NaOH alone and with the addition of MEA were undertaken to understand the influence of the addition of MEA on the pulp viscosity. The result for the pulp obtained with 12% NaOH alone (control) showed shear thinning with the increase of shear rate from 0 to 100 s^{-1}; the sample viscosity decreased from 188 Pa.s to 0.145 Pa.s (Fig. 5a). For pulp obtained with 12% NaOH and with the addition of MEA 30%, with the increase of shear rate from 0 to 100 s^{-1}, the sample viscosity decreased from 93.9 Pa.s to 0.0087 Pa.s (Fig. 5b). It was also observed that with the addition of MEA 30%, there was a decrease in initial pulp viscosity from 188 Pa.s for the control to 93.9 Pa.s with the additive, showing an increase in cellulose degradationFurther, the rheological study of the pulp with a decrease in NaOH concentration from 12% to 9%, while keeping the MEA additive constant at 30%, was undertaken. The viscosity of pulp with the increase of shear rate from 0 to 100 s^{-1} decreased from 66600 Pa.s to 0.102 Pa.s (Fig. 5c). It was observed that with the decrease in NaOH from 12% to 9%, and keeping the MEA additive constant at 30%, and with the increase in shear rate from 0 to 100 s^{-1}, there was a significant increase in pulp initial viscosity from 188 Pa.s for 12% NaOH to 66600 Pa.s for 9% NaOH, then showing a decrease in cellulose degradation.

The pulp viscosity showed non-Newtonian, shear-thinning flow behavior, and the sample's viscosity decreased with the increase in the shear rate. The higher viscosity at lower shear rates indicates that the cellulose fibrils are entangled, leading to more hindering interactions between the fibrils and a decrease in their mobility, which ultimately results in higher viscosity measurements.[47]

The control pulp obtained with 12% NaOH exhibited 188 Pa.s viscosity at near-zero shear rate, followed by a sharp drop as the shear rate increases, stabilizing around 0.145 Pa.s at 100 s^{-1}. In comparison, the sample treated with 9% NaOH and 30% MEA demonstrated higher initial viscosity than the control. This suggests that the addition of MEA at a lower alkali charge promotes stronger initial intermolecular interactions within the pulp suspension. The high viscosity and the high yield observed in the MEA pulps, even after cooking at high temperatures, can be attributed to the carbohydrate-stabilizing effect of MEA. The sample obtained with 12% NaOH with 30% MEA exhibits very low viscosity, which indicates that the sample is relatively fluid under these conditions. This indicates that the 30% MEA charge at higher alkali concentration substantially increases delignification, confirmed by the low kappa number, but with increased cellulose breakdown, whereas at low NaOH concentration and with MEA 30% charge, there was not much change in kappa number, but there was significantly lower cellulose degradation.

CONCLUSION

This study provides a comprehensive evaluation of MEA as an additive in soda pulping of depithed sugarcane bagasse, enabling alkali reduction and delignification. On adding MEA additive with soda pulping there was a decrease in pulp rejects and kappa number and an increase in cellulose content. In alkaline pulping under control conditions with 12% alkali alone and after addition of 30% MEA charge, there was a reduction in kappa number from 37.53 to 15.57, pulp rejects reduced from 1.67% to 0.34%, and the cellulose content increased from 88.22% to 93.86%. Positive effects of MEA in pulping were brought about by the prevention of cellulose degradation, which resulted in pulps with higher cellulose content due to the uniquely high selectivity of MEA in lignin dissolution. Experimental results demonstrate that the addition of MEA at concentrations up to 30% significantly enhances delignification, reducing pulp rejects and preserving cellulose content. The rheological analysis revealed that MEA influences pulp viscosity profiles, with higher viscosity at lower alkali charges, indicating reduced cellulose degradation and improved integrity. Overall, the results confirm that MEA functions as an effective pulping additive that enhances delignification selectivity, reduces high alkali charges, and improves cellulose preservation at lower alkali charges. Applying MEA as an alkali source in soda pulping is also very effective. It reduces the need for high alkali charges in pulping, making it a promising alternative in soda pulping processes and opening new perspectives for non-wood fibers like bagasse. Future studies should explore life cycle assessment and MEA recovery in a continuous system to support industrial implementation.

ACKNOWLEDGMENTS: The authors acknowledge Dr. Renu Singh IFS, Director, Forest

Research Institute, Dehradun, India, for providing facilities for the research work at the Cellulose Paper Discipline, Forest Products Division. The authors are grateful to the Century Pulp and Paper Mill, Lalkaun, Nainital, Uttarakhand, India, for kindly providing samples of depithed sugarcane bagasse.

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