Lignin Reattachment to Pulp Fibers during Brownstock Washing: The Role of Sodium Sulfate

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The role of sodium sulfate was considered relative to pulp washing liquors and its impact on the reattachment of lignin to pulp fibers during the brownstock washing process. The dissolution of lignin during washing and its potential redeposition onto the pulp fibers is influenced by various factors. Three distinct types of pulp - unbleached, bleached, and cotton linters - were used to explore these effects. The washing experiments were conducted using industrial wash liquor and were repeated further with the addition of sodium sulfate. The resulting products of the washing process, including the liquor discharge and the washed pulp, were thoroughly evaluated. Analytical techniques, such as UV measurements of lignin content in the liquor discharge and characterization of the pulp, were employed to assess the outcomes. The findings reveal that the addition of sodium sulfate to the washing liquor resulted in an increase in its conductivity and ionic strength. Moreover, it was observed that lignin reattachment to pulp fibers was noticeably greater when washing was performed with sodium sulfate addition. Among the pulps studied, unbleached kraft pulp exhibited the highest degree of lignin reattachment, followed by bleached kraft pulp, with cotton linters showing the least.

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INTRODUCTION

Over the past decades, kraft pulping has become the most important method for producing pulp for paper, board, and other applications from wood (Ragnar *et al*. 2014). Therefore, optimizing unit operations and utilizing byproducts are of vital interest. One often overlooked unit operation is brownstock washing, which involves washing the freshly produced pulp using alkaline liquors from oxygen delignification. Efficient brownstock washing of kraft pulp improves chemical recovery and reduces the environmental footprint, thereby enhancing overall mill performance (Santos and Hart 2014). Today, pulp mills are increasingly adopting system closure strategies to minimize the net water consumption in the fiberline process. However, the counter-current recycling of liquors to the washing stages can have adverse effects, such as the reattachment of lignin to the pulp fibers, ultimately affecting the final product's quality (Koljonen *et al*. 2004; Suarez 2024). This phenomenon, known as lignin redeposition, occurs in the kraft process and involves the reattachment of dissolved lignin and other extractives from black liquor onto cellulose fibers in the pulp. Such redeposition can significantly impact subsequent processing stages, product quality (bleachability), and environmental performance (chemical consumption) (Maximova *et al*. 2004).

Lignin transport and adsorption are critical in kraft pulping and biorefinery processes (Ghaffari *et al.* 2024). Dissolved and partly degraded lignin can aggregate or adsorb onto fibers due to chemical and physical forces influenced by pH, ion strength, and temperature. During kraft cooking, lignin dissolves in black liquor due to the solution’s high alkalinity and ionic strength. However, as pH decreases during washing, lignin’s colloidal stability is reduced, promoting precipitation and redeposition onto the pulp fibers (Suarez 2024). Lower pH diminishes the negative charge on lignin molecules, leading to coagulation and deposition. Significant precipitation occurs at pH values below 6, where lignin forms a granular layer on pulp surfaces, with acidified conditions shown to increase surface lignin content by up to four times compared to alkaline environments. Similarly, extractives can precipitate under acidic conditions, forming thin surface films that are often washed away during sheet forming (Koljonen *et al*. 2004). In addition to the pH effect, high concentrations of multivalent metal ions can induce the precipitation of dissolved lignin and extractives (Björklund-Jansson *et al*. 1985; Sundin and Hartler 1998; 2000).

Previous studies have shown that metals, particularly calcium and magnesium, contribute to lignin precipitation by forming complexes with oxalates, increasing their surface concentrations and promoting lignin flocculation on fiber surfaces under lower pH (Maximova *et al*. 2004). Calcium ions were found to facilitate lignin aggregation and adsorption by neutralizing the negative charges on lignin particles, with high calcium concentrations significantly enhancing flocculation on fiber surfaces. Maximum lignin uptake occurs when lignin flocs become electrically neutral (Li *et al*. 2019). Among various cations, calcium has been found to promote lignin sorption in alkaline solutions more effectively than others. Electrostatic and colloidal interactions primarily drive lignin adsorption onto pulp fibers (Maximova *et al*. 2001, 2004). Lower pH further promotes lignin precipitation by decreasing solubility and increasing molecular aggression. While calcium and magnesium ions are particularly effective in supporting lignin deposition under alkaline conditions, sodium ions show the least impact. Only high molecular weight lignin was precipitated, as its large size reduced solubility and increased Van der Waals attractions (Sundin and Hartler 2000). Acidification is the primary driver of lignin and extractive precipitation, whereas metal ions (Ca^{2+}, Mg^{2+}) play a secondary, supportive role. These metals, especially calcium and magnesium, become more soluble at lower pH levels because acidic environments dissolve precipitated carbonates and deposits, thereby increasing their concentrations in solutions. Increased lignin content resulted in darker, less bright pulp sheets. Elevated surface-to-bulk ratios of lignin indicated that metals accumulated primarily on the surface rather than being evenly distributed throughout the pulp forming thick lignin layers. In addition, thin extractive films have been reported to modify fiber surface chemistry and to reduce bonding potential (Koljonen *et al*. 2004).

Kraft lignin solubility and stability in alkaline solutions are critical for kraft pulping and subsequent washing processes. Higher pH promotes lignin solubility, thereby reducing the risk of deposition. The pKa of phenolic hydroxyl groups in lignin is approximately 10; thus, as the falling pH approaches this level, the phenolic groups become protonated and lose their charge. The loss of ionic stabilization promotes lignin aggregation and deposition on pulp fibers. These factors have been reviewed by (Hubbe *et al.* 2019). High ionic strength – particularly from divalent cations like Mg^{2+} and Ca^{2+} – reduces lignin stability in the solution and promotes redeposition. Adjusting the liquor's ionic strength before washing can help maintain lignin solubility and minimize precipitation. Elevated temperatures can enhance diffusion but may also encourage the aggregation of lignin. This framework helps to explain ion-specific differences in kraft lignin precipitation, including cation-specific effects, Hofmeister effects, and the combined influences of cations and anions (Norgren and Edlund 2003). At high salt concentrations – especially in the presence of sulfates – ion effects on lignin solubility closely follow the trends described by the Hofmeister series (Senthilkumar *et al.* 2024). Sodium sulfate (Na_2SO_4) has been shown to reduce diffusion rates at high concentrations, which is likely due to lignin aggregation (Ghaffari *et al.* 2024). Inadequate displacement of black liquor can result in higher lignin concentrations in contact with the pulp, thereby increasing the risk of redeposition. Higher lignin content in the washed pulp can reduce brightness and compromise strength properties (Małachowska *et al.* 2020). During washing, temperature and ionic strength influence the lignin solubility, with certain conditions favoring its deposition. The fiber's surface charge and porosity also affect lignin's tendency to adhere to the fiber surface (Maximova *et al.* 2004). Electrostatic repulsion between lignin and fiber diminishes in high-ionic-strength solutions, further promoting redeposition (Suarez 2024).

The aqueous environment itself can significantly influence the aggregation and stabilization of lignin particles, in addition to the pH dependent ionization of the phenolic hydroxyl groups in lignin. Recent studies have shown that the size, charge characteristics, and morphology of lignin nano-precipitates are determined by several factors, including pH, ionic composition, and molecular interactions (Trovagunta *et al.* 2024; Barrios *et al.* 2025). In the context of brownstock washing, where variations in solution chemistry dictate whether lignin remains dispersed or redeposits onto fiber surfaces, these self-assembly phenomena are expected to be important.

Redeposited lignin increases the demand for bleaching chemicals, leading to higher operational costs and a more significant environmental impact. Excessive redeposition can also contribute to scaling and fouling in downstream equipment (Ulmgren 1997). Preventing lignin precipitation requires maintaining stable pH levels and elevated temperatures during washing and controlling ionic strength to avoid conditions that promote lignin aggregation and deposition. Effective washing also depends on optimized equipment design, robust process control, and, when necessary, additives. Modelling efforts are essential to meet modern kraft pulp mills' evolving operational and sustainability demands (Santos and Hart 2014).

Furthermore, the chemical structures present on the fiber surface also influence lignin redeposition. In addition to uncharged polysaccharides, which exhibit some affinity for aromatic structures such as lignin, there are also charged polysaccharides, such as pectins and xylans (Sjöström 1993), as well as lignin covalently bound to polysaccharides (so-called lignin-carbohydrate complexes (LCCs)) (Lawoko *et al.* 2004). These different surface components are likely to interact with lignin distinctly, making variations in pulp surface composition an essential factor affecting lignin redeposition.

The purpose of this study was to investigate the impact of sodium sulfate addition to the washing liquor on lignin redeposition during the brownstock washing process, with a particular focus on how fibers with different chemical compositions—namely unbleached kraft pulp, bleached kraft pulp, and cotton linters—respond to these conditions. By examining the interplay between sodium sulfate, fiber surface chemistry, and process parameters such as pH and ionic strength, this study aims to deepen the understanding of lignin behavior during washing and identify factors contributing to redeposition, which is critical for optimizing pulp quality and improving mill performance.

MATERIAL AND METHODS

Materials

Commercial-grade unbleached mixed softwood pulp (Norway spruce, *Picea abies*, and Scots pine *Pinus sylvestris*) and washing filtrate (FTA) from the wash press of a commercial mill were supplied by the Swedish pulp company, SCA Östrand mill. Fully bleached mixed softwood pulp from commercial production was provided by Södra. Washing Filtrate (FTB) was prepared in the laboratory by adding various amounts of 1 M Na_2SO_4 to the FTA. Cotton linter was obtained from Crane (Stockholm, Sweden). The pulp sheets were cut into smaller pieces, suspended in water, and disintegrated. All chemicals used were of analytical grade.

Methods

The chemical composition of the raw materials used in the washing experiments is shown in Table 1. Figure 1 provides an overview of the procedure. The high cellulose content of cotton linters cellulose indicates their naturally high purity (>95%) (Palme 2017). The unbleached pulp data from SCA Östrand mill come from the work of Starrsjö *et al.* (2021). Thermogravimetric analysis (TGA) was used to determine the ash content in each raw material.

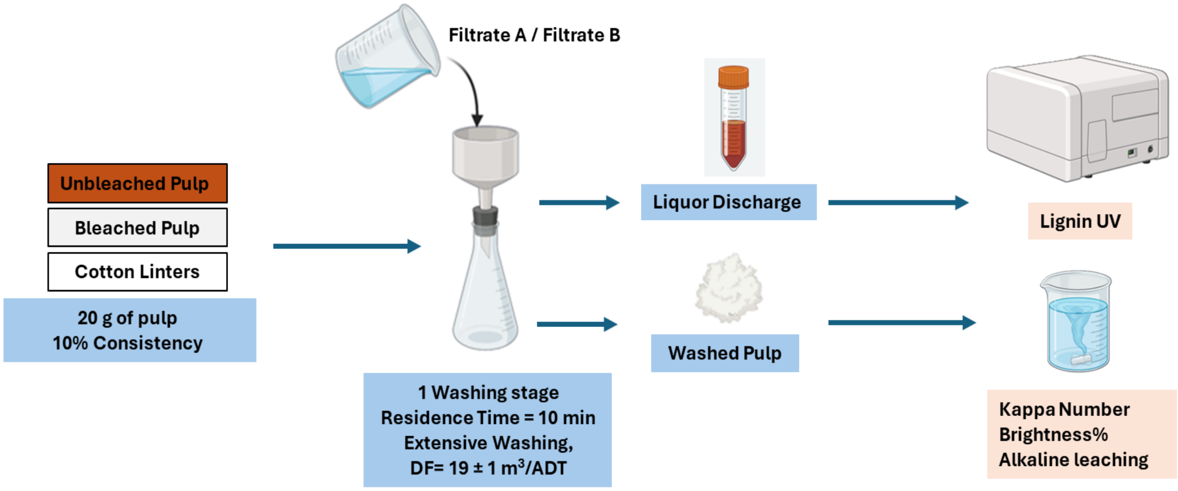

Fig. 1. The scheme used in this study to perform the washing experiments

Table 1. Chemical Composition of Raw Materials

Composition of Pulp (%)	Unbleached Pulp	Bleached Pulp	Cotton Linters
Lignin%	4.1	<0.5	<0.5
Cellulose%	77.4	84.5	>95%
Glucomannan%	7.8	5.7	
Xylan%	9.0	8.2	
Galactoglucomannan%	0.4	0.2	
Ash%	1.24	0.23	0.55

* The data for the composition of cotton linters comes from Palme (2017).
** The data for unbleached pulp and bleached pulp were supplied by SCA Östrand mill and Södra, respectively.

Table 2. Fiber Morphology of Raw Materials

Pulp Type	Mean Length Weight (mm)	Mean Length Arithmetic (mm)	Mean width (µm)	Mean Shape factor (%)	Mean Fines (%)
Unbleached	2.1 ±0.01	1.4	31.5	84.5	10.9±0.28
Bleached	2.2 ±0.01	1.2±0.01	29.5±0.07	79.3±0.07	18.7±0.35
Cotton Linters	1.7	1.0	23.1	77.5	22.3±0.70

The fiber morphology of the raw materials, including fiber length and width, is shown in Table 2. Unbleached fibers exhibited the lowest fines content and were relatively straight, wide, and moderately long. The bleached pulp had slightly more curled fibers (lower shape factor) and a higher fines content but showed the longest mean fiber length (length-weighted). Cotton linters displayed the lowest shape factor, the highest fines content, and the shortest and narrowest fibers – characteristics typical of high-purity papers made from cotton linters. The slightly longer mean fiber length in the bleached pulp compared to the unbleached pulp may be attributed to variation among industrial samples.

Laboratory scale washing

A Büchner funnel with a diameter of 128 mm and a pore size of 2.1 mm was used for lab-scale washing. The washing procedure consisted of a single stage with a residence time of 10 min. As illustrated in Fig. 1, each washing experiment was conducted at a 10% pulp consistency, with a dilution factor of 19 ± 1 (m^3/ADT), using 20 g of unbleached pulp, bleached pulp, or cotton linters. The wash liquors used in the experiments were FTA and FTB, as described in Table 3. A UV-Vis 2550 spectrophotometer (Shimadzu, Japan) was used to measure lignin content in the liquor discharges, while the washed pulp was analyzed for brightness, Kappa number, and alkaline leaching.

Table 3. Wash Liquor Characteristics

Wash Liquor	pH	Conductivity (mS/cm)	Lignin (mg/g OD pulp)	1M Na_2SO_4 (mL)
FTA	11.35±0.06	32.88±0.13	337.91±0.72	0
FTB	11.27±0.04	40.60±0.46	317.58±0.72	50

FTA – Washing filtrate from the SCA Östrand mill industry; FTB – FTA + 50 mL of 1M Na_2SO_4.

Alkaline leaching

About 1.0 g of washed pulp (dry weight) was transferred to an oil bath containing 100 mL of 0.1 M NaOH, stirred at 80 °C, and left to leach for 1 minute. The mixture was dewatered using a Büchner funnel and a 100 µm nylon cloth. The same filtrate was passed again through the pulp cake, followed by dewatering of the pulp and final displacement with 50 mL of deionized water at 80 °C. The pulp was collected, and filtrates from alkaline leaching and displacement washing were combined, weighed, and analyzed by UV-Vis.

UV-Vis spectroscopy

The filtrates from the washing stage were passed through a 110-mm filter paper before being analysed for lignin by absorbance of UV radiation. A 1.0 mL sample was diluted with deionized water as needed. The extractable lignin content was determined by measuring absorbance at 280 nm using a Shimadzu UV-2550 spectrophotometer. The absorbance of each washing filtrate was measured at 280 nm and calculated using Eq. 1,

$$Lignin\ \left(\frac{mg}{g\ OD\ pulp}\right) = \frac{(A_{280nm} - A_{600nm}) * \mathrm{DF} * \mathrm{V}}{\text{Ɛ} * \mathrm{b} * \mathrm{P}} \tag{1}$$

where $A_{280\mathrm{nm}}$ denotes absorbance value at 280 nm, $A_{350\mathrm{nm}}$ is absorbance value at 350 nm, DF indicate dilution factor, V is the volume of filtrate (mL), Ɛ is molar absorptivity coefficient (L/g*cm), b is length (cm), and P denotes OD pulp weight (g).

Brightness measurement

Before filtration, the washed pulp was diluted, treated with 0.5 mL of EDTA per gram of pulp, and disintegrated. Handmade sheets (200 g/m^2) were prepared according to the TAPPI T 218 standard. The wet web was pressed for one minute using a Testing sheet press 40140. The pulp sheets were dried and conditioned at 25 ± 2 °C and 50 ± 2% relative humidity (RH) prior to analysis. Brightness was measured using the integrating sphere mode of the UV-2550 spectrophotometer, with pulp brightness defined as the reflectance of paper at 457 nm. The brightness percentage was determined using ISO 2470-1:2016.

Kappa number

Following washing, the pulp's Kappa number was determined according to ISO 302:2015 (E), which specifies the method for measuring the residual lignin content in the pulp. The measurements were performed using a Mettler Toledo T70 automatic titrator.

Scanning electron microscopy

The surface morphology of the pulp fibers was analyzed using a field emission scanning electron microscope (FE-SEM, Hitachi S-4800, Japan). Before imaging, the fibers were thoroughly dried and mounted on a stub using conductive carbon adhesive tape.

Thermogravimetric analysis

Thermogravimetric analysis (TGA) was performed using a Mettler Toledo TGA 1 instrument at a heating rate of 10 °C min^{-1} in an oxygen atmosphere, with a purge rate of 50 mL min^{-1}. The temperature range was from 50 to 800 °C. Samples were first isothermally heated at 150 °C for 15 minutes to remove solvent residues, and then they were cooled to 50 °C and subsequently heated to 800 °C to determine the thermal decomposition maxima (T_d), the temperature at 5% weight loss (T_5), and the char yield. TGA data were analyzed using Mettler Toledo STARe software, version 15.00.

Fourier transform infrared spectroscopy

FTIR analysis was conducted using a PerkinElmer Spectrum 100 FTIR spectrometer. Spectra were recorded in the range of 4000 to 500 cm^{-1} with a resolution of 4 cm^{-1}, averaging 32 scans per sample. The analysis focused on identifying sulfate-related absorbance bands and monitoring changes in the composition of the black liquor.

Fiber morphology

Fiber morphology was analyzed using the Lorentzen &Wettre (L&W) fiber tester. The instrument suspends fibers in an aqueous flow strong enough to orient them in two dimensions without deformation. A digital imaging system captures and analyzes fiber images, and the software calculates morphological parameters such as fiber length, fiber width, shape factor, and number of kinks.

RESULTS

Experiments were performed on three types of washed pulps: one unbleached pulp containing covalently bound lignin on its surface along with hemicelluloses, one fully bleached pulp with almost no lignin but still containing hemicelluloses, and cotton linters that are practically free of both lignin and hemicelluloses. The pulps were washed with industrial washing liquors (FTA) containing lignin and other organic material removed from the pulps. Additionally, the experiments were repeated (on separate samples) using the same washing liquor with added sodium sulfate (FTB). Absorbance at 280 nm was measured for the discharged liquors (Fig. 2). The results indicated that more lignin was absorbed into the bleached and unbleached wood-derived pulps than onto the cotton linters and that the presence of sulfate ions increased the adsorption. The unbleached pulp adsorbed slightly more material than the bleached pulp, but the difference was small.

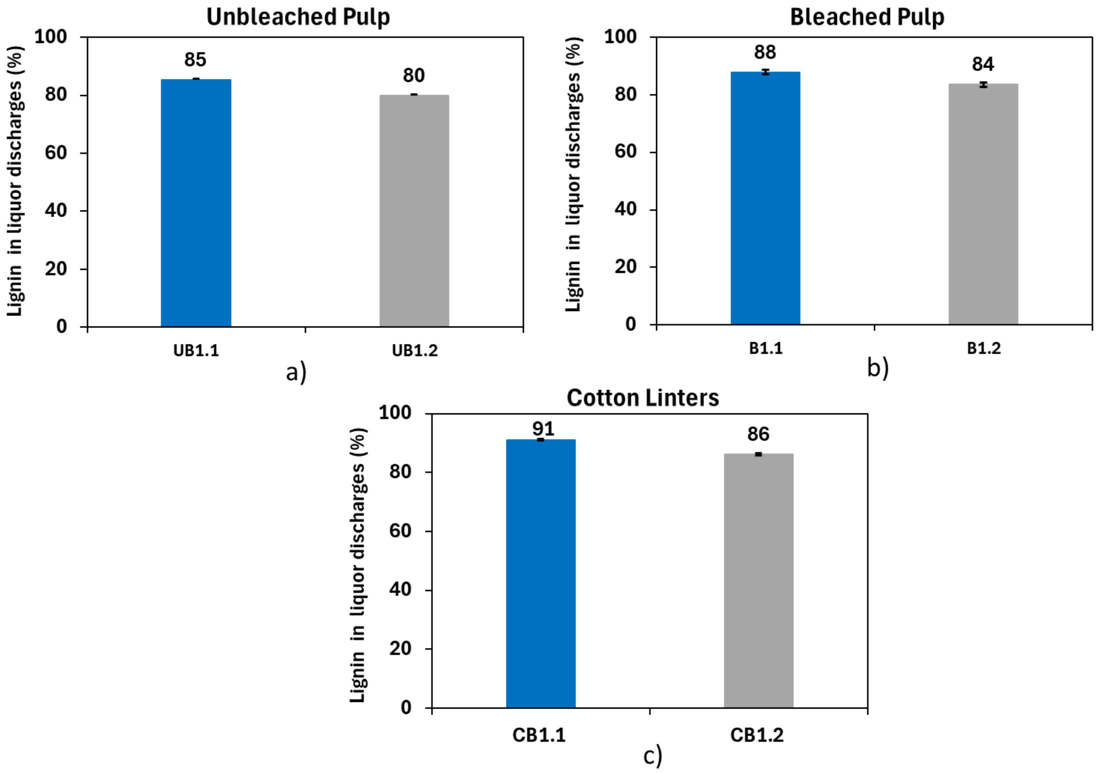

Fig. 2. Lignin (%) for the liquor discharges from the washing experiments, measured at 280 nm. a) UB1.1: UB1.2 - Unbleached pulp washed with filtrates (FTA and FTB), b) B1.1: B1.2 - Bleached pulp washed with filtrates (FTA and FTB), c) CB1.1: CB1.2 - Cotton linters pulp washed with filtrates (FTA and FTB).

The pulps with adsorbed lignin were leached with sodium hydroxide, and the released material was analyzed with UV spectrometry (Fig. 3). The results confirmed that more material was released from the bleached and unbleached pulps than from the cotton linters. However, significantly less UV-absorbing material was leached from the bleached pulp compared to the unbleached pulp when washed with added sodium sulfate.

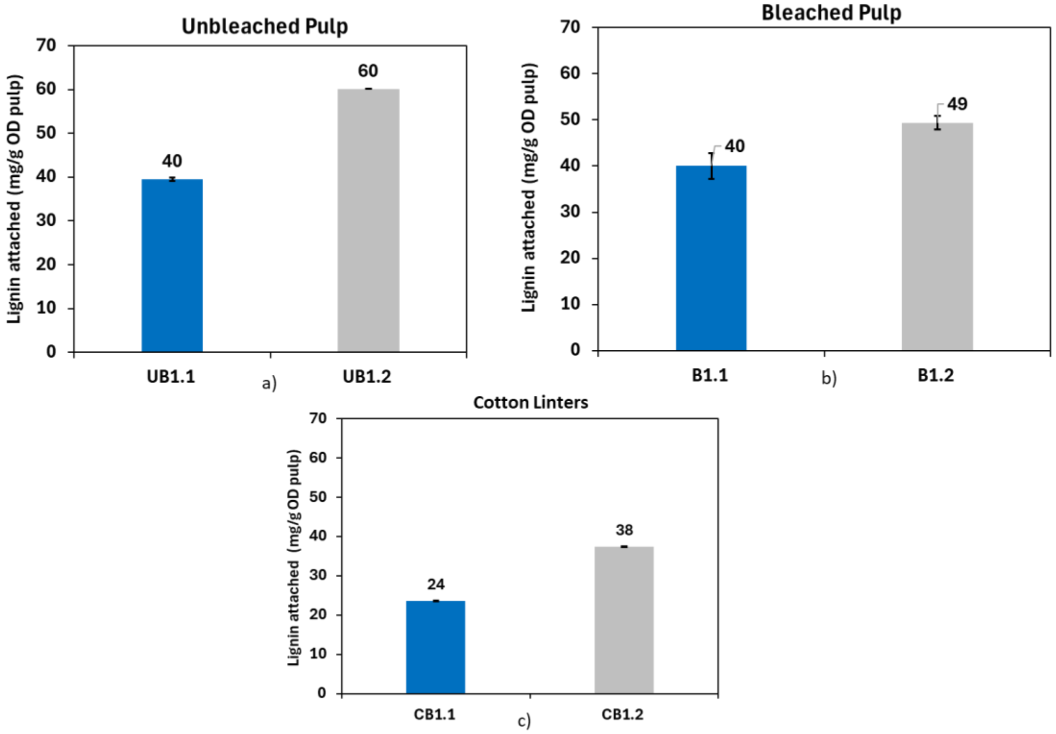

Fig. 3. Alkaline leaching for different washed pulps. a) UB1.1: UB1.2 - Unbleached pulp washed with filtrates (FTA and FTB), b) B1.1: B1.2 - Bleached pulp washed with filtrates (FTA and FTB), c) CB1.1: CB1.2 - Cotton linters pulp washed with filtrates (FTA and FTB).

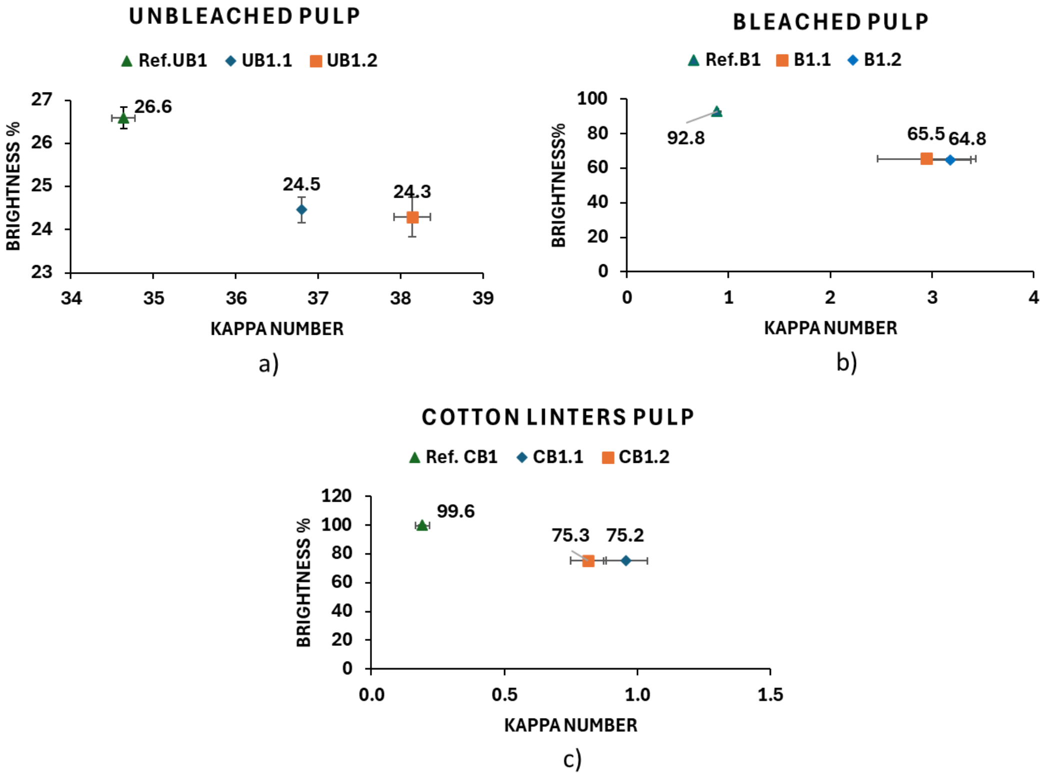

Fig. 4. Kappa number and brightness for different washed pulps: a) UB1.1: UB1.2 - Unbleached pulp washed with filtrates (FTA and FTB), b) B1.1: B1.2 - Bleached pulp washed with filtrates (FTA and FTB), c) CB1.1: CB1.2 - Cotton linters pulp washed with filtrates (FTA and FTB)

The brightness and kappa number of the pulps (before the leaching) were also analyzed (Fig. 4). The results indicated that washing increased the kappa number for all samples, particularly those washed with sulfate. A similar trend was observed for brightness.

Figure 5 highlights the absorbance spectra of the washing filtrates (FTA and FTB), with key regions corresponding to major functional groups. In the characteristic sulphate regions (~1100 cm^{-1}), distinct differences were observed between the two spectra: the FTB filtrate exhibited higher absorbance, consistent with the addition of sodium sulfate. In contrast, the FTA filtrate showed lower sulfate-related absorbances, suggesting a more effective removal of these components during washing.

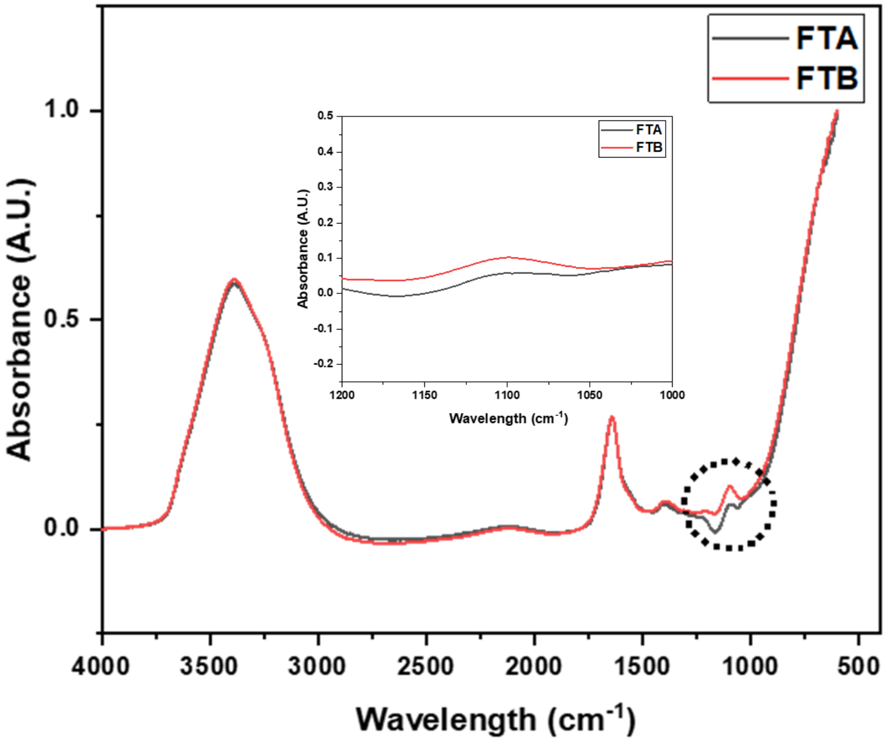

Fig. 5. FTIR spectra of washing liquors (FTA and FTB).
FTA: Industrial wash liquor from SCA Östrand mill, FTB: FTA + 50 mL of 1M Na_2SO_4.

The FE-SEM analysis (Fig. 6) revealed structural differences in the pulp fibres following the washing experiments. The results indicate that lignin redeposition was more pronounced in the unbleached and bleached pulps than in cotton linters. Additionally, the presence of sulfate ions likely promoted fiber bundling and lignin reattachment.

The unbleached pulp (Fig. 6A) appeared heterogeneous, with intact fiber bundles and surface debris, likely corresponding to lignin deposits. Washing with FTA resulted in smoother fibers with more distinct individual structures. However, the pulp washed with added sodium sulfate, (Fig. 6C) showed increased fiber bundling and surface debris. This revealed the occurrence of lignin reattachment promoted by the presence of sodium sulfate. Furthermore, the bleached pulp (Fig. 6D) displayed a cleaner, more fibrillated surface than unbleached samples. When washed with FTA, the bleached pulps remained open but appeared denser (Fig. 6E). This shows increased agglomeration and deposition when washed with added sodium sulfate (Fig. 6F), highlighting the role of sodium sulfate in promoting lignin reattachment. In contrast, the cotton linters (Fig. 6G) exhibited a fine, fibrillated structure with minimal residues. Washing with FTA (Fig. 6H) had little to no effect, whereas washing with FTB (Fig. 6I) resulted in slight fiber bundling, accompanied by limited reaccumulation of lignin.

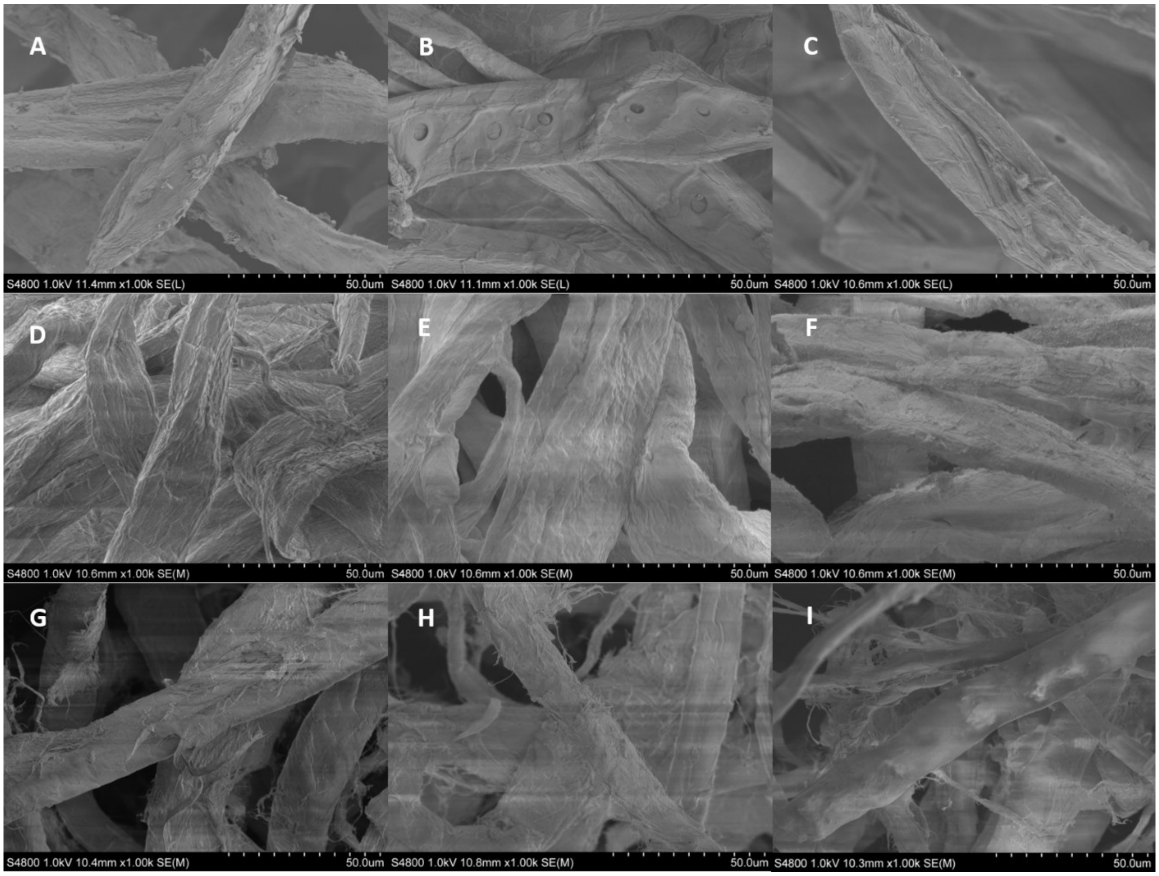

Fig. 6. FE-SEM images of various pulp samples: (A) Unbleached pulp-REF, (B) Unbleached pulp washed with filtrate FTA, (C) Unbleached pulp washed with filtrate FTB, (D) Bleached pulp-REF, (E) Bleached pulp washed with filtrate FTA, (F) Bleached pulp washed with filtrate FTB, (G) Cotton linters pulp-REF, (H) Cotton linters pulp washed with filtrate FTA, and (I) Cotton linters pulp washed with filtrate FTB. FTA refers to the washing filtrate obtained from the industry (SCA Östrand mill), while FTB corresponds to FTA combined with 50 mL of 1M Na_2SO_4

DISCUSSION

During brown stock washing, lignin redeposition has a significant impact on pulp quality, bleachability, and washing efficiency. This study examined the mechanisms governing lignin redeposition and the factors that influence its extent. Lignin redeposition primarily occurs due to the solubility of dissolved lignin fragments in black liquor and their interactions with cellulosic fibers. These interactions may include electrostatic interactions (ion-ion, ion-dipole, dipole-dipole), hydrogen bonding, and apolar interactions, such as Van der Waals bonds, charge transfer (aromatic π-stacking), and hydrophobic interactions. The latter two interactions are enhanced by salts such as sodium sulfate, which is positioned early in the Hofmeister series (Köhn *et al*. 1996). Since adding sulfate ions increases adsorption, it is plausible that apolar interactions primarily drive lignin readsorption. Parameters such as temperature, pH, ionic strength, the presence of surfactants, and dissolved organic matter all influence lignin solubility and redeposition (Gellerstedt 2015). The hydrophobic and aromatic nature of lignin, combined with its affinity for cellulose fibers, promotes adsorption, especially under conditions favourable for precipitation (Sjöström 1993).

Cotton linters consist solely of cellulose, which has a high degree of crystallinity and exposes few hydrophobic surfaces.

Bleached softwood kraft pulp also contains more amorphous hemicellulose with more exposed hydrophobic groups, along with traces of remaining covalently bound lignin.

The unbleached pulp contains both hemicellulose and remaining lignin, bound through lignin-carbohydrate complexes (LCC) to the fiber.

During washing, cotton linters are exposed to lignin degradation products and other organic matter containing apolar structures.

During washing, bleached softwood kraft pulp is exposed to lignin degradation products and other organic matter containing apolar structures.

During washing, unbleached pulp is exposed to lignin degradation products and other organic matter containing apolar structures.

Since the exposed hydrophobic areas in the highly crystalline cellulose are small, relatively modest amounts of material bind, and rather weakly.

In bleached softwood kraft pulp, more hydrophobic surfaces are exposed, and the amount and binding strength of the organic matter are higher.

The unbleached pulp contains remaining lignin with aromatic structures. These will form rather strong interactions with the organic matter in the liquor.

Fig. 7. Schematic presentation of a hypothetical explanation for the variations of readsorption on lignin to different pulps

In this study, cotton linters adsorbed less material than wood-based pulp. As discussed, hydrophobic and aromatic interactions are crucial in lignin adsorption onto fibers. While aromatic structures in lignin can interact with monosaccharide residues, interactions between two aromatic structures are likely stronger. Cotton linters lack aromatic structures, whereas wood-based pulps – especially unbleached pulp – contain lignin covalently bound in lignin-carbohydrate complexes (LCCs), providing aromatic sites for interaction. Additionally, amorphous polysaccharides, such as hemicelluloses, expose more hydrophobic surfaces than highly crystalline materials (von Schreeb *et al*. 2025). This further supports the observation that adsorption is more substantial on wood-based pulps than on cotton linters (Fig. 7). From this perspective, the washing of partially bleached pulps shows similarities to hydrophobic interaction chromatography (Queiroz *et al*. 2001).

Key washing parameters, including wash water temperature, dilution factor, displacement ratio, and pH control, strongly influence lignin redeposition (Suarez 2024). Alkalinity affects lignin solubility, and a drop in pH can trigger lignin precipitation, increasing the risk of redeposition (Kayal *et al*. 2025). Maintaining an optimal pH range helps minimize precipitation, ensuring effective lignin removal. Elevated lignin content in washed pulp increases chemical consumption during bleaching, raising operational costs and environmental impact (Santos and Hart 2014). Additionally, redeposited lignin can stiffen fibers, negatively affecting paper brightness and formation. The composition of the washing liquor further influences redeposition dynamics. Effective washing requires careful control of ionic strength to prevent lignin precipitation. Adjusting the liquor's ionic strength before washing helps maintain lignin in solution (Lindström 1980). Excessive lignin redeposition reduces pulp brightness and weakens strength properties. It also increases the demand for bleaching chemicals and contributes to scaling and fouling in downstream equipment.

Lignin redeposition is a complex phenomenon influenced by multiple process conditions. However, optimized washing parameters and targeted chemical interventions can significantly reduce lignin carryover, improving pulp quality, and decreasing bleaching chemical consumption. Further research into advanced washing technologies and real-time monitoring could offer additional strategies to mitigate lignin redeposition in industrial pulp washing operations.

Technical Significance

The data from this study support the view that pulp washing in mills is a system that includes multiple stages and a cluster challenge. Since pulps are washed in counter-current systems, where washing liquors from a later stage are reused in an earlier stage. The wash liquors in brown stock washing contain substantial amounts of lignin degradation products that can adsorb onto the pulp, as demonstrated in this study. This adsorption increases the load on the oxygen delignification and bleaching stages. Apolar interactions, such as hydrophobic and aromatic interactions, play a significant role in lignin redeposition. This is particularly problematic because the sulfate ions present in the oxygen delignification process (where oxidized white liquor is used as the alkali) are known to strengthen these interactions. Reducing the content of dissolved organic matter and sulfate ions in the wash liquors used for brown stock washing could potentially improve the efficiency of this process. However, achieving such improvements in an industrial setting remains a significant challenge.

CONCLUSIONS

1. Lignin and other organic matter were adsorbed onto unbleached and bleached softwood kraft pulps, as well as cotton linters, when washed with industrial washing liquors containing lignin.

2. The adsorbed organic matter was bound to the fibers primarily through apolar interactions, including hydrophobic and aromatic interactions.
3. Lignin reattachment to the pulp fibers was significantly greater when washing was performed with added sodium sulfate.
4. The addition of sodium sulfate increased the ionic strength of the washing liquor, which negatively affected washing efficiency by promoting lignin redeposition.
5. Among the pulps tested, unbleached kraft pulp exhibited the highest lignin reattachment, followed by bleached kraft pulp, while cotton linters showed the lowest.

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