A targeted approach to produce energy-efficient packaging materials from high-yield pulp

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ABSTRACT: Unlike fossil-based plastics, wood-based packaging materials can be produced in an ecofriendly manner using wood chip residuals from sawmills and pulpwood. To produce high-yield pulp like chemithermomechanical pulps (CTMPs) for paperboard and liquid packaging, it is crucial to reduce the electric energy consumption during fiber separation. The ultimate objective is to revolutionize paperboard production by achieving a middle-layer CTMP process that consumes less than 200 kilowatt-hours per metric ton (kWh/t), significantly improving from the current 500–600 kWh/t energy demand.

Optimizing the CTMP impregnation process of sodium sulfite (Na_2SO_3) in wood chips is crucial for achieving uniform softening, ideally at the fiber level. The properties of the fibers are significantly affected by the content of lignin sulfonates within the walls of the fiber and the middle lamellae. In this study, we employed in-house developed X-ray fluorescence (XRF) techniques, validated by beamline measurements, to map the distribution of sulfonated lignin within fibers. It also seemed possible to enhance the surface area of lignin-rich pulp fibers while losing minimal bulk by refining them with well-optimized low consistency (LC) refining. We aimed to achieve a highly efficient separation of coniferous wood fibers by co-optimizing the sulfonation and the temperature in the preheater and chip refiner. Additionally, we explored how lignin's softening behavior and potential crosslinking influence subsequent unit operations, including pressing, peroxide bleaching, and drying, following the defibration process. In defibration during chip refining, the maximum softening of wood fibers is preferred to maximize fiber preservation and minimize energy consumption. However, optimizing the stiffness of finished pulp fibers is preferable to reduce bulk loss during paperboard production. It can strive to optimize processes to develop stronger, lighter, and more sustainable composite packaging materials. Reducing environmental impact and electric energy can help create a more sustainable future.

Application: This article discusses advancements in the CTMP process to create lightweight paperboard products that enhance strength and stiffness while maintaining consistent bulk. Techniques such as sulfonation, optimized refining, and low-consistency refining help preserve fiber morphology and increase fiber surface area without sacrificing bulk. This innovation addresses key challenges and promotes renewable, ecofriendly packaging as a sustainable plastic alternative.

The awareness regarding plastic pollution and its detrimental impact on ecosystems, particularly marine environments, has grown significantly in recent years. In response, the development of lightweight and functional bio-based materials is gaining momentum to replace traditional fossil-based plastics. To ensure these alternatives are sustainable, biodegradable bio-fibers derived from wood pulp must be produced with high resource efficiency. This can be achieved by increasing the use of high-yield pulps (with yields exceeding 95%) while minimizing reliance on chemical pulps, which typically have lower yields (around 50%). High-yield pulps, such as chemithermomechanical pulp (CTMP) and high-temperature CTMP (HTCTMP), are becoming increasingly favored in packaging applications, especially for food and beverages, as they enable innovative packaging solutions that preserve product quality and reduce waste across supply chains [1,2]. By adopting such materials for paperboard production, the packaging industry can align with global goals to reduce marine pollution, including the United Nation's Sustainable Development Goal 14.1, which aims to minimize marine contamination by 2025. These efforts underscore the importance of transitioning from disposable plastic packaging to resource-efficient, high-yield pulp-based alternatives.

Global annual consumption of fresh fiber pulp is about 179 million metric tons, with 107 million metric tons directly integrated into paper or paperboard production [3]. In 2022, the Swedish forest industry utilized 69.5 million cubic meters of domestic raw material and imported 6.3 million. Half of this material is used for sawn timber, while the rest supports pulp and paper mills. Sawmills provide raw materials for wooden boards, pulp and paper production, and energy [4]. Sweden exports fresh fiber to Europe, where raw material availability is more limited. This fiber is reused multiple times in paper production.

The CTMP systems using softwoods or mixtures of soft-

woods and hardwoods usually use 10–30 kg/metric tons of sodium sulfite (Na_2SO_3) in an impregnator before preheating to soften the wood chips using lignin sulfonation. Lignin content is highest in the middle lamellae, which is a key to fiber separation during the fiber separation in chip refining. Chemical (sulfonation) and thermal softening above lignin's glass transition temperature (T_g) enable efficient fiber separation in the CTMP process [5]. However, disparities in chemical uptake between the surface and core fibers of wood chips lead to uneven softening, affecting product quality and process efficiency [6].

Our trials highlighted challenges with lignin softening distribution, particularly in the core fibers, which remain undertreated. Addressing this requires precise measurement of fiber properties, such as softness, wall thickness, and morphology. Advancing our understanding of lignin behavior during defibration and its role in packaging applications will be critical. By improving the efficiency of chemical utilization and achieving uniform lignin softening, CTMP could be produced with lower chemical charge and better combinations of functional properties, enhancing performance and expanding its application range. A more even distribution of sulfonation on the fiber level would probably allow for more defibration into well-separated fibers at lower energy demand. As the fibers emanating from the wood chip surface would not have an unnecessarily high sulfonation degree, even sulfonation could enable an improved bulk at a specific strength, which is highly desirable for various applications, such as sustainable packaging [1,2,7]. The challenge in developing the unit process is ensuring that chemicals effectively penetrate the inner parts of the wood chips. Currently, the technology results in a significantly higher concentration of chemicals in the fibers near the surface than in the center of the wood chips [8,9]. Pretreatment methods, such as high-pressure compression screws or pre-refining techniques like those used in the advanced thermomechanical pulp (ATMP) process, can partially address this issue [10-12]. However, these methods often fail to separate fibers cleanly along the middle lamella, which is crucial for creating very bulky sheets used in products like packaging boards and hygiene materials. Moreover, insufficient sulfonation in the outer fiber wall layers can cause fractures in the secondary cell wall, exposing carbohydrate-rich surfaces that alter the fiber bonding properties [13]. This inconsistency leads to higher shives content (unseparated fibers) in the final pulp, reducing overall quality [1,9]. We hypothesize that the efficiency and uniformity of fiber separation in the refining process are directly tied to how evenly the wood chips are sulfonated [1,5,8]. Reducing sulfonation variability between fibers could lower the sulfite required while achieving the desired degree of fiber separation. To advance this process, it is essential to understand the spatial distribution of sulfur within CTMP pulp fibers. Visualizing this distribution requires advanced tools capable of delivering high spatial and spectral resolution to study sulfonation at the microscopic level [1,9].

As an alternative, optimized low consistency (LC) refining can enhance the surface area of lignin-rich pulp fibers while reducing bulk loss [14,15]. Separating fibers while maintaining their inherent stiffness is essential in chip refining. This requires optimizing conditions that influence the softening of wood chips and employing refiner fillings designed for efficient processing [14-16]. Low consistency refining can produce fibrillar fines, also known as secondary fines [14,17], significantly improving the network strength while preserving bulk [14,18,19]. Research has demonstrated that higher fibrillar fines content enhances paper strength [20]. This effect is attributed to the ability of fibrillar fines to reinforce the bonds within the fiber network. Therefore, we aim to optimize the conditions for LC refining, focusing on developing improved or novel LC refiner filling patterns. The objective is to produce more fibrillar fines, increase the fiber surface area, and enhance fiber separation while preserving as much stiffness as possible.

Further, softened lignin is crucial in enhancing interfiber bonding, even in wet conditions, by redistributing within the fiber matrix [21,22]. Our investigation into lignin softening and crosslinking across processes like pressing, peroxide bleaching, and drying highlights its function as a natural wet-strength additive. Previous studies show that applying isolated lignin to paper and pressing it at high temperatures significantly improves interlayer bonding and overall strength, with effectiveness influenced by the type of lignin, applied temperature, and moisture levels [23,24]. Water-saturated lignin begins to soften around 115°C, a process further enhanced by sulfonation [25]. More recently, Joelsson et al. demonstrated that sulfonation facilitates lignin softening in sulfite-enriched paper during hot pressing, allowing for strength retention at lower temperatures [21]. These findings underscore lignin's potential as a sustainable and effective material enhancer for CTMP.

In summary, all these studies focus on optimizing CTMP processes by enhancing the strength and stiffness of paperboard while reducing its weight by increasing the bulk of the middle layer. Our collaboration at Valmet's Sundsvall, Sweden, pilot plant and Mid Sweden University focused on optimizing sulfonation, pH control, preheating, and refining temperatures. Our goal is to achieve controlled softening of fiber walls, which could lead to new opportunities as a targeted approach in sustainable and lightweight packaging solutions.

METHODS AND MATERIALS

Pulp preparation

Persson et al. conducted a pilot-scale trial at the Valmet Technology Centre in Sundsvall to explore efficient methods for separating coniferous wood fibers [16]. Spruce wood chips (Norway spruce) were provided by Billerud's Rockhammar Mill in Sweden.

The production process began with presteaming the wood chips at atmospheric pressure for approximately 15 min, during which the chips were heated to 90°C. The

Parameter	Value	Unit
Chemical Addition		
Sodium sulfite (Na_2S_{03})	23	kg/bdt
Bound sulfur, S_B	1.4	g/kg
Total sulfur, S_T	9.0	g/kg
System Conditions		
pH	7.1	-
Temperature	130	°C
Residence time	2	min
System pressure	170	kPa
Energy Usage		
Specific energy consumption (SEC)	1135	kWh/bdt
Refining Parameters	0.25	mm
Refining gap		
Pulp Properties		
Canadian Standard Freeness (CSF)	5.62	mL
Fiber length (FL)	mL	mm
Shives content	1.42	%

kg/bdt: kilograms per bone-dry metric ton; kWh/bdt: kilowatt hours per bone-dry metric ton

I. Valmet's specialized pilot trial data on processes and fibers.

chips were then fed into an impregnator using a plug screw, which served as a seal against the pressure inside the impregnator. As steam condensed on the chip surfaces during this process, their moisture content increased, reducing the dry matter content from around 50% (for fresh chips) to approximately 30%. In the plug screw stage, about 1 m³ of liquid was expelled per ton of dry solids, and the chips in the impregnator reabsorbed an equivalent amount of liquid. Due to the smaller dimensions of the plug screw in the pilot plant, the chips underwent more intensive mechanical processing compared to those in full-scale plants. This treatment resulted in a more tattered chip structure and a higher liquid absorption rate in the pilot plant than in full-scale operations.

The impregnator was integrated into the preheater system, and the impregnated chips overflowed into the preheater, where they were subjected to a dwell time of 2 min. From the preheater, the chips were transferred directly to the refiner via a feed screw rotating at 300 rpm, located 300–400 mm from the refiner inlet. Unlike full-scale plants, the pilot plant lacked an intermediate plug screw, resulting in direct connectivity between the preheater and the refiner. Consequently, all released chemicals, substances, and chips entered the refiner. This arrangement also contributed to a lower chip dry content than full-scale systems. The refining process utilized an OVP20 single-disc refiner with a 20-in. disc diameter and standard segment 5811 operating at 1500 rpm. The refined fibers and steam were separated via a blow line connected to an atmospheric cyclone. Various characteristics of the produced pulps were analyzed, including shive content, freeness, fiber length (PQM), crill content, pH, chemical oxygen demand (COD), total sulfur, and bound sulfur. The impregnator and preheater operated at 130°C during the process. **Table I** provides additional details regarding operating conditions.

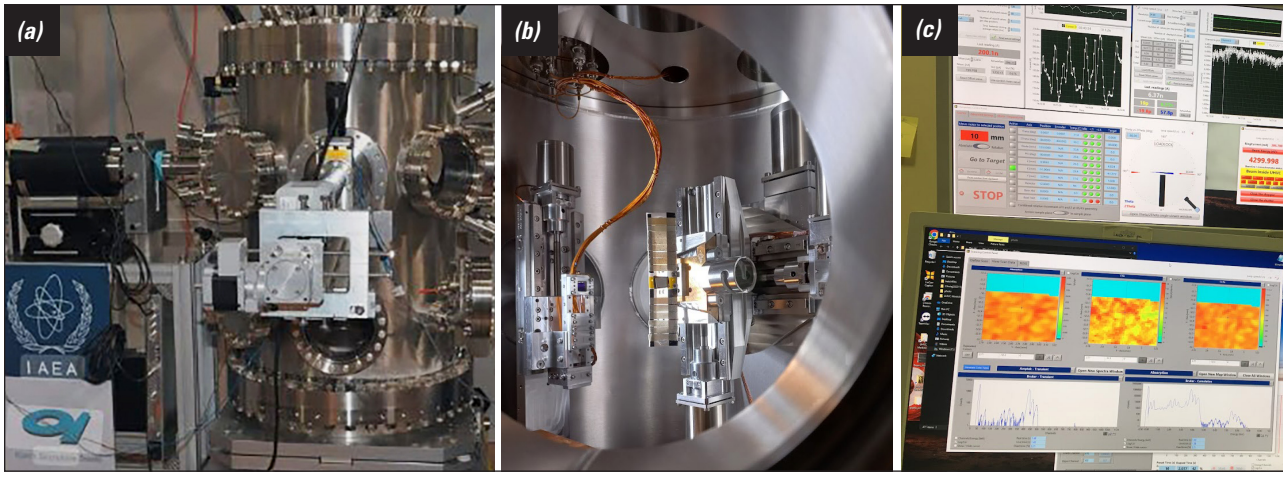
Two pilot trials were also conducted by Berg et al. [14] on first-stage CTMP (from Billerud's Rockhammar Mill) at the Valmet Technology Centre in Sundsvall using a low-consistency JC00 conical pilot refiner (Valmet; Espoo, Finland). The refining process utilized two types of filling patterns: the "standard fillings" (type JC00RAD2/JC00SAD2) and a fine pattern (type JC00RMM15Z/JC00SMM15Z). During each trial, the pulp was pumped through the refiner from one chest to another, with the refining gap adjusted to achieve specific refining energy and intensity levels. Pulp samples were collected at six different refining gaps. **Table II** provides additional details regarding operating conditions.

Handsheet preparation

Handsheets were produced using a Rapid Köthen sheet former (Paper Testing Instruments; Pettenbach, Austria) following the guidelines outlined in ISO 5269-2:2004 "Pulps — Preparation of laboratory sheets for physical testing — Part 2: Rapid-Köthen method." The fiber suspension was prepared with a stock consistency of 6.0 g/L. Before form-

Refiner Filling	JC00 Standard	JC00 Fine	Unit
Width of bar (*W*)	4.0	1.3–1.4	mm
Bar angle (α)	18	33–15	°
Cutting edge length (*CEL*)	1.8	10.1	m/rev
Specific edge load (*SEL*)	0.68–2.0	0.075–0.29	J/m
Rotation speed (ω)	1200	1200	rpm
Temperature	56	60	°C
Pulp consistency (*C*)	4.3	4.1	%
Flow through the refiner	200	200	L/min
Idle load	20	30	kWh/t
Net refining energy (*SRE*)	48–142	29–118	kWh/t

II. Low consistency refining conditions.



1. X-ray fluorescence (XRF) analysis of chemithermomechanical (CTMP) handsheets at the Elettra beamline in Italy: (a) IAEAXspe end station installed at the XRF beamline; (b) CTMP sheets in a vacuum chamber at XRF; and (c) display of sulfur image mapping.

ing the sheets, the fiber suspension was vigorously aerated by passing compressed air through the stock at a flow rate of 60 L/min. This step, conducted immediately before sheet formation, ensured uniform dispersion as specified by the ISO standard. The handsheets were formed with a 100 g/m² grammage and then press-dried at 94°C with a pressure of 100 kPa until the sheets reached a moisture content of 45%–50%.

After drying, the sheets were carefully sealed in plastic bags and stored at room temperature for approximately 24 h. This stabilization period ensured consistent material properties before proceeding with advanced analyses. The stabilized sheets were then utilized for experiments such as X-ray fluorescence (XRF) analysis in the laboratory and at the Elettra Synchrotron facility in Basovizza, Italy, and detailed imaging through scanning electron microscopy (SEM).

For these tests, 10 samples were investigated out of 20 total, while six samples were selected for synchrotron sulfur mapping due to beamtime limitations. Each sample was analyzed at multiple spot sizes to capture variability. For SEM analysis, two samples were examined at different locations to ensure representative data. This thorough sample preparation ensured reliable and reproducible material properties for subsequent experiments, including advanced sulfur imaging and mechanical testing.

SEM analysis

High-resolution SEM using the Tescan Maya3-2016 (Tescan; Brno, Czechia) was employed to analyze the CTMP sheets. The sheets were hot-pressed using planar pressing equipment at 180°C and 3.5 MPa for 10 min, with a moisture content of 25%, before pressing. Imaging was carried out with an electron beam voltage of 3.00 kV, and a beam intensity of 1.00 was used at a magnification of 2000x. The working distance between 5 mm and 7 mm was maintained to ensure optimal image quality. Cross-sections of the samples were prepared using argon ion milling with the Hitachi IM4000Plus (Hitachi; Tokyo). Before imaging, the samples were sputtered with a 5–10 nm iridium layer.

Advanced XRF capabilities at the Elettra beamline

The IAEA Xspe end station at the Elettra beamline is designed for advanced XRF measurements. It features ultra-high vacuum (UHV) chambers with a sample transfer system, motorized stages, and a seven-axis manipulator for precise positioning. The end station includes two silicon drift detectors (SDDs) for XRF and gallium arsenide (GaAs) and silicon (Si) photodiodes for beam monitoring. A microscope and camera are mounted at a 45° angle to the synchrotron beam and detector axis, providing a field of view of approximately 5 mm² × 4 mm² for XRF analysis. We analyzed our CTMP paper sheets with a spatial resolution of 50 µm at the Elettra XRF beamline, using X-ray energies ranging from 2–14 keV, as illustrated in **Fig. 1**.

RESULTS AND DISCUSSION

Refining gentleness

Building on the Valmet pilot trials described previously, Berg et al. [15] introduced two new parameters — equivalent temperature related to softness, ET_S, and refining gentleness, G — that consider key factors such as actual operating temperature, the softening temperature of fibers, bound sulfonate content, and the refining gap, providing a more comprehensive approach to refining optimization [15]. The ET_S (°C) and G were proposed as:

$$ET_s = T + 6.4\ S_b$$
$$G = ET_s\ \ g/D$$

where:
T = actual temperature, °C
S_b = bound sulphonate content, g S/kg
g = refining gap, m
D = refiner diameter, m

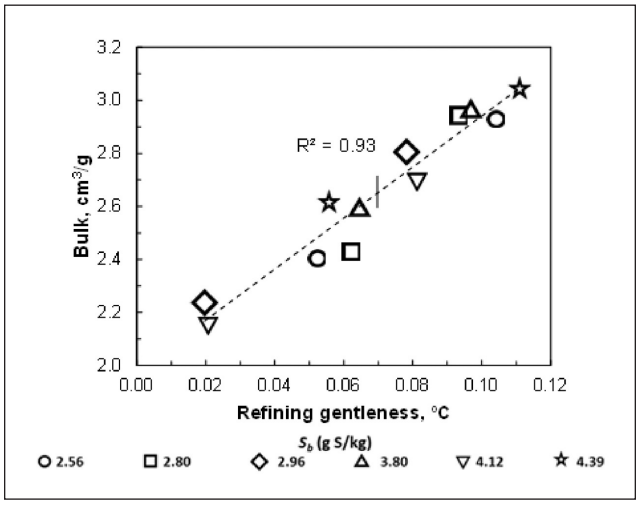
Bound Sulfur (S_B) g/kg	Sodium Sulfite, kg/bdt	Preheating Temperature, °C	Refining Gentleness, °C	Bulk, cm³/g	Tensile Index, Nm/g	Z Strength, kPa	Shives Content, %	Fiber Length, mm	Freeness (CSF), mL
2.56	25	160	0.104	2.93	13.0	87.7	3.86	2.12	770
2.80	25	140	0.093	2.94	15.0	103.4	3.27	2.10	758
3.80	50	140	0.097	2.97	12.7	105.0	9.23	2.14	763

III. The summary of pulp properties and refining conditions observed at refining gentleness values between 0.09°C and 0.10°C.

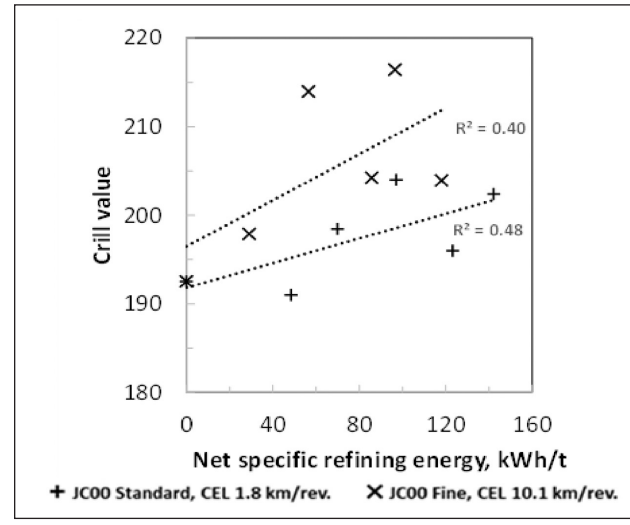
As detailed in **Table III**, refining gentleness values from 0.09°C–0.10°C produced comparable pulp properties. **Figure 2** illustrates a linear correlation between bulk and refining gentleness.

Enhancing strength properties through LC refining

Fine-patterned fillings with narrow bar widths in LC refining have been shown to enhance the strength properties of CTMP while preserving its bulk. Berg et al. observed that the tensile index of spruce CTMP, taken from the discharge of a pilot-scale JC00 refiner, improved from 30.2 Nm/g with standard fillings to 32.6 Nm/g with fine-patterned fillings [14]. Similarly, the Z-strength increased from 238 kPa to 255 kPa. Interestingly, the specific refining energy remained nearly constant at 91 kilowatt-hours per metric ton (kWh/t) for standard fillings and 92 kWh/t for fine fillings, indicating the potential for energy efficiency with the finer patterns. Other characteristics, such as freeness, average fiber length, and shives content, remained unchanged. However, the crill value (unwashed) showed a slight increase, rising from approximately 200 to 210, as depicted in **Fig. 3**. This increase in strength is likely attributed to the production of additional crill in the fine-patterned fillings. All properties were measured at a bulk of 2.3 cm³/g, reinforcing the potential of fine fillings to optimize CTMP refining without compromising bulk.



2. Pilot-scale trials were conducted at varying bound sulfonate content and bound sulfur (SB) levels. The error bars on the regression line represent the mean standard deviation for bulk, calculated as 0.06 cm³/g (R²: coefficient of determination).



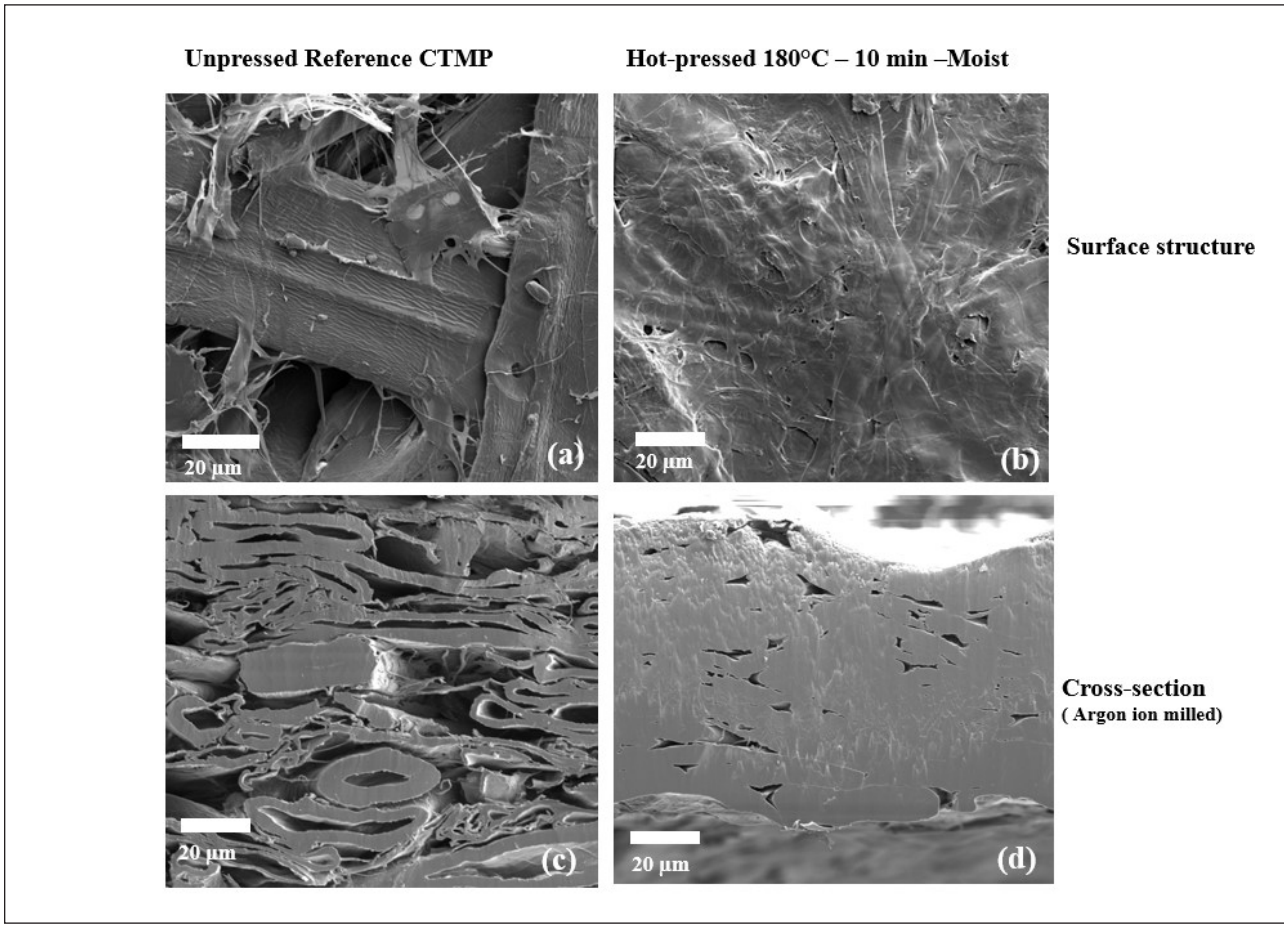
3. The unwashed crill value (measured using PulpEye; Örnsköldsvik, Sweden) is plotted against net refining energy, comparing two fillings with different cutting-edge length (CEL).

We hypothesize that LC refining can improve fiber-fiber bonding while reducing bulk loss due to surface fibrillation.

Visual insights into fiber changes driven by pressing process

Hot-pressing is an effective technique for enhancing lignin-containing paper's wet and dry strength. The wet strength significantly increases with higher pressing temperatures, achieving optimal improvement between 180°C and 270°C [22]. This enhancement is primarily due to the interdiffusion of lignin macromolecules, which accelerates as the temperature rises, driven by an activation energy of approximately 26 kJ/mol [22]. A key challenge in this process is managing the redistribution of lignin within the fiber networks without damaging hemicelluloses or other polymers. Furthermore, the combination of high temperature and moisture content before hot pressing can induce structural changes in the material. These changes are analyzed using SEM to understand their effects on mechanical properties.

Figure 4 presents SEM images comparing CTMP paper sheets in their pressed and unpressed states. The unpressed reference sample (Fig. 4a) exhibits a porous structure characterized by fibers retaining their typical oval



4. The scanning electron microscope (SEM) images depict the structural characteristics of CTMP paper sheets: (a) the unpressed reference sample, and (b) a sheet hot-pressed at 180°C for 10 min under 3.5 MPa while moist. The SEM cross-sectional images, polished using an argon ion milling machine, are also shown for (c) the unpressed reference sample, and (d) the hot-pressed at 180°C for 10 min under 3.5 MPa while moist. The working distance for all samples during imaging was maintained between 5 mm and 7 mm.

shape. In contrast, the CTMP moist sheets (25% moisture) pressed at an elevated temperature of 180°C for 10 min under 3.5 MPa (Fig. 4b) show a significant transformation, with fibers consolidating into ribbon-like structures and their lumens nearly entirely closed. The differences in porosity among the samples are most evident in SEM cross-sectional images prepared by polishing the samples using an argon ion milling machine. Inter-fiber pores and partially open fiber lumens are visible in the unpressed reference sheets (Fig. 4c). In comparison, most of the lumens appear collapsed in the moist CTMP sheets hot-pressed at 180°C for 10 min (Fig. 4d), although their structure remains partially discernible.

Hot pressing at 180°C significantly alters the surface and internal structure of the CTMP sheet. The SEM analysis shows a reduction in porosity and increased fiber consolidation. These changes result in improved structural integrity and higher densification than the unpressed reference sheet. As a result, the mechanical properties of the sheet are enhanced, demonstrating greater strength in both dry and wet conditions. The mechanical properties of these sheets, determined according to the following standard test methods: ISO 534:2011 "Paper and board — Determination of thickness, density and specific volume"; ISO 536:2019 "Paper and board — Determination of grammage"; ISO 1924-3:2005 "Paper and board — Determination of tensile properties — Part 3: Constant rate of elongation method (100 mm/min)"; and ISO 9895:2008 "Paper and board — Compressive strength — Short-span test". These mechanical properties are presented in **Table IV**. However, it is essential to carefully control the hot-pressing process to avoid potential damage to the material. Further testing is needed to quantify the exact impact on mechanical performance.

Visualizing sulfur in CTMP sheets via XRF at Elettra

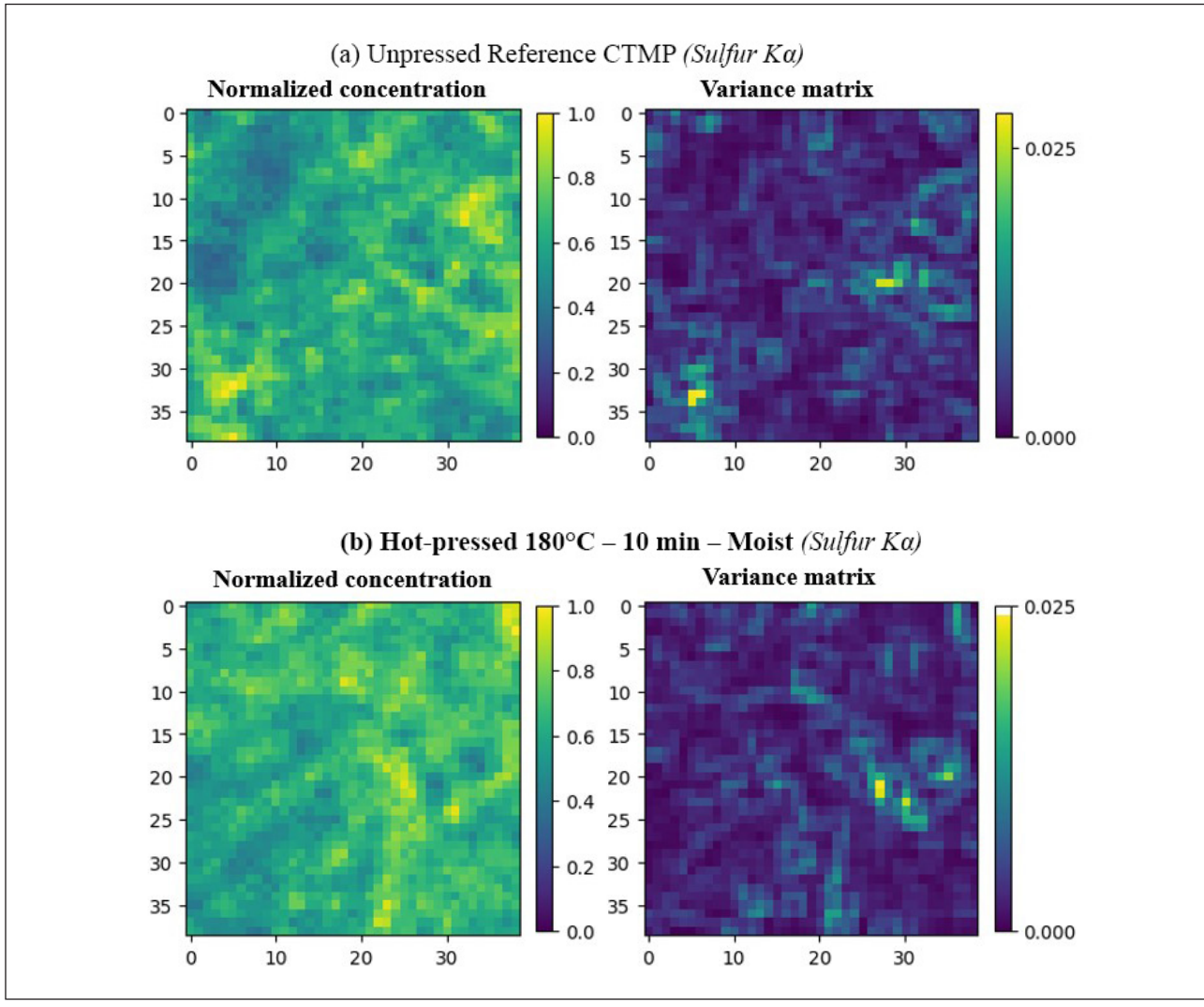
Mapping the micro-scale distribution of sulfonates in wood fibers and chips is challenging due to surface irregularities, low fluorescence yields, and the inefficiencies of conventional X-ray sources. Previous XRF measurements [1,8] revealed difficulty detecting sulfur, compromising intensity

	Unpressed	Hot-pressed
Density, kg/m³	483.5	867.4
Dry tensile strength, Nm/g	27.8	57.5
Wet tensile strength, Nm/g	*	16.9
SCT index, Nm/g	15.8	45.5
* Not possible to measure		

IV. Mechanical properties of two different CTMP handsheet samples: an unpressed reference and a sample hot-pressed at 180°C for 10 min under moist conditions (SCT: short-span compression test).

and resolution. To address this, we utilized synchrotron radiation at Elettra in Italy, which provides a more intense beam and improved resolution for precise sulfur mapping. This study evaluates the hypothesis of uneven sulfonation and explores optimal spatial resolution for reproducible, reliable onsite measurements.

The sulfur distribution maps in **Fig. 5** were created using XRF scans conducted at the XRF beamline at Elettra (2–14 keV range, operated at 4.3 keV, optimized for sulfur's Kα emission). The setup included an XFlash 5030 SDD-detector (Bruker Nano GmbH; Berlin, Germany) with a zirconium (Zr) collimator, resulting in a 25-mm² active crystal area and 131 eV resolution (at MnKα). In the unpressed reference CTMP sample (Fig. 5a), sulfur distribution is highly heterogeneous, with yellow regions indicating elevated sulfur content and blue showing lower concentrations. This variability, confirmed by the variance matrix, likely stems from surface irregularities and incon-



5. Sulfur distribution maps of CTMP sheets via advanced XRF analysis at the Elettra beamline.

sistent sulfonate impregnation. No directional trends were observed, suggesting random dispersion. In the hot-pressed CTMP sample (180°C, 10 min moist) (Fig. 5b), sulfur distribution remained heterogeneous. Still, it showed subtler high-concentration regions, indicating sulfonate redistribution due to thermal and mechanical compression structural changes. The variance matrix for the hot-pressed sample indicates reduced variability in some areas, suggesting partial homogenization of sulfur content while showing increased clustering in others. This is likely due to localized condensation or chemical interactions triggered by the pressing conditions. This indicates that hot-pressing affects sulfur allocation, even if subtle in the provided maps, although complete uniformity is not achieved.

Both samples demonstrate inherent non-uniformity of sulfur distribution in CTMP fibers, with hot-pressing causing localized sulfonate redistribution while maintaining some degree of heterogeneity. These findings highlight the impact of thermal and mechanical factors on sulfur dynamics, impacting other material properties such as mechanical strength, chemical reactivity, and fiber bonding. The XRF measurements at Elettra enabled precise mapping of microscale compositional variations, allowing for a detailed understanding of sulfonation patterns. Although the hot-pressed sample does not show complete uniform sulfur distribution, the data indicate that adjustments in processing could improve sulfur homogeneity and enhance material performance.

CONCLUSION

This study explores the production of high-performance CTMP-based materials by optimizing refining and chemical treatments to improve mechanical properties and energy efficiency. Fine-patterned fillings in LC refining significantly enhance the strength properties of CTMP without compromising bulk, likely due to improved fiber-fiber bonding and slight increases in crill content. Our data demonstrate that these refining strategies can optimize mechanical pulps for high-performance applications while maintaining energy efficiency and bulk properties. This study underscores the importance of uniform softening of wood chips through lignin sulfonation to enable better fiber separation and bonding.

Using synchrotron-based XRF at the Elettra beamline, we mapped sulfur distribution in CTMP handsheets at 50 µm resolution, revealing highly heterogeneous patterns in both unpressed and hot-pressed samples (180°C, 10 min, moist, 3.5 MPa). Hot-pressing led to partial redistribution of sulfur but did not fully homogenize the allocation. Visual analysis and variance matrices highlighted localized high-concentration zones and subtle shifts in variability, suggesting that mechanical and thermal treatments influence sulfonation patterns but cannot completely overcome the challenge of uniform sulfur distribution. This challenge directly impacts fiber bonding, chemical efficiency, and overall material performance. Advanced microscale analysis, such as XRF, is essential to understand these subtle variations and guide future process improvements.

Although current treatments modify sulfonation distribution, further optimization in refining, pressing conditions, and chemical treatments is needed to achieve uniform distribution. Such improvements would be a significant step toward creating more sustainable, high-performance CTMP-based materials with better mechanical performance, durability, and energy efficiency. **TJ**

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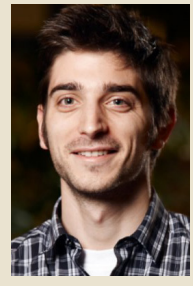
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Our research is focused on the urgent need for sustainable packaging solutions that can replace fossil-based plastics and help combat marine pollution. We are pioneering the development of lightweight, high-strength paperboard packaging materials that are ecofriendly and energy efficient by optimizing the chemithermomechanical pulping (CTMP) process. Our approach minimizes environmental impact by using high-yield pulps (HYP) with yields exceeding 95% while addressing key energy consumption and fiber separation challenges.

A central aspect of our work involved improving the impregnation of sodium sulfite (Na_2SO_3) into wood chips for uniform sulfonation, which is essential for effectively softening the lignin in core fibers. We employed in-house X-ray fluorescence (XRF) to enable precise mapping of sulfonated lignin, optimizing fiber morphology for enhanced mechanical properties. Refining conditions such as low-consistency (LC) refining and lignin crosslinking maximized fiber surface area and interfiber bonding, resulting in more substantial, lighter, and defect-free packaging. This approach also reduced energy consumption to under 200 kWh/metric ton — significantly lower than current industry standards — while enhancing fiber preservation and stiffness.

For mills, this approach ensures bulk retention, wet-strength enhancement, and scalability, paving the way for developing renewable, high-performance composite structures. This work aligns with global sustainability goals and presents a transformative alternative to traditional plastic packaging, meeting the growing demand for renewable, low-carbon materials with minimal environmental impact.

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