Recycling performance of softwood and hardwood unbleached kraft pulps for packaging papers

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ABSTRACT: The scope of this work is to evaluate the recyclability potential of hardwood and softwood unbleached kraft pulps, leading to a sound basis for comparison and even to support a decision about fibers according to the performance achieved. The influence of successive recycling cycles (up to 10 cycles) on the fiber morphology, pulp suspension drainability, water retention capacity, and handsheet mechanical properties were studied for *Eucalyptus globulus* and *Pinus sylvestris* unbleached kraft pulps. The performance of these pulps as linerboard and corrugating medium for packaging was also evaluated. The requirements for brown kraftliner and for high performance recycled fluting grades is preserved for *E. globulus* pulp during all 10 recycling cycles, evidenced by the moderate decrease of burst index and crush resistance index and by the short-span compression index, whereas the *P. sylvestris* pulp loses this rating after the second cycle. These results strongly support the higher performance of *E. globulus* pulp for recycling as compared with softwood kraft pulp from the perspective of packaging papers.

Application: Considering the growing demand for packaging papers, as well as the circular economy global trend, careful selection of raw fibers must take into consideration their recyclability potential. Unbleached *Eucalyptus globulus* fibers succeed in preserving key functional properties for a higher number of recycling cycles.

The relevance of the pulp and paper sectors to the circular economy and recyclability is reflected in the total world recycling rate of 58.6% in 2019, with Europe at 72.5% and North America at 65.7%. The recycling rate is defined as the ratio between used paper recycling (including net trade of paper for recycling) and paper and paperboard consumption [1]. However, the potential for the recyclability of paper is not unlimited, as virgin fibers lose their properties throughout the recycling cycles [2,3]; in practice, paper is recycled up to 3 to 5 times [4]. Thus, it is essential to renew the fiber cycle by introducing virgin fiber in the process, namely for the production of high-quality paper. Depending on the paper and board grades to be produced, there is a need to introduce different types of fibers, including short fiber, of which *Eucalyptus globulus* is a very successful example, long fibers, and recycled fiber, in addition to mineral fillers and other process and functional additives. For packaging, unbleached softwood kraft fiber is among the most widely used fibers, primarily in linerboard [5], but hardwood kraft fibers can also play an important role. Therefore, evaluation of these different virgin fibers in the recycling process would support decisions in raw material selection and to anticipate impacts from multiple recycling cycles on paper properties.

The topic of paper recycling has been the subject of intense research, and there is a consensus that there is a continuous loss of mechanical strength in paper structure and increasing difficulty in drainage with the increase of recycling. Recycling introduces irreversible changes in structural, physical, and chemical properties of the fibers, the so-named fiber hornification [6]. Hornification phenomena mainly affect low-yield chemical pulps [7], reducing swelling capacity, conformability, water retention value, wet flexibility, and bonding potential of fibers [8]. This phenomenon results mainly from the irreversible collapse of a substantial part of the pores existing in the cell wall of the never-dried virgin fibers during paper production, namely, under drying [5,9,10]. Several mechanisms have been proposed as the cause for pore collapse during drying, such as capillary forces, fibrils lying down irreversibly onto the fiber surface, and rearrangement of ultrastructural fibril elements due to thermal softening [5]. The fibers lose hydration capacity, and consequently, the wet fiber flexibility [11] and collapsibility are diminished [5]. These effects lead, in general, to more open paper structures, with much lower fiber specific bonded area and therefore lower mechanical strength. As the fiber is less flexible and less hydrated, it is expected that more fine elements will be produced when subjected to the beating process, provoking higher suspension drainage resistance.

Evaluation of the recycling potential of pulp has mainly been focused on softwood in several key areas: analyzing the effects on the morphology of the fibers and the production of fine elements; water retention value; the usual mechanical strengths (tensile, tear, burst, fold endurance); and the optical-structural properties [3,4,12]. However, the packaging paper and paperboard global production has increased in recent years, as evidenced by an average 2.8% growth per year between 2010 and 2018 [13], with even higher prospects for the future as a means to replace fossil-based plastic by paper, board, and other cellulosic materials, wherever possible. In this context, the demand for fiber sources and recycling will foster the utilization of fibers from both hardwoods and softwoods for containerboard paper grades. Therefore, it is necessary to evaluate the property requirements according to the definitions for each grade [14].

With recycled paper increasingly accepted as an important fiber source for producing liner and fluting, some recent published works have focused on the recyclability of corrugated base papers and the impact of the number of loops in the final papermaking properties. Kreplin et al. [15] tested recycling of corrugated based papers for up to 15 cycles and concluded that paper fibers can be recycled more times than typically expected, without significant loss of strength properties. Eckhart et al. [16] carried out a similar recycling study on folding boxboard, and results also showed no negative effect on the mechanical properties after 25 recycling cycles. However, these studies are based on laboratorial methodology at conditions far different from those applied in the industrial recycling process, where cellulosic fibers are also subjected to refining (low intensity) and drying processes during papermaking that have additional impact in final properties.

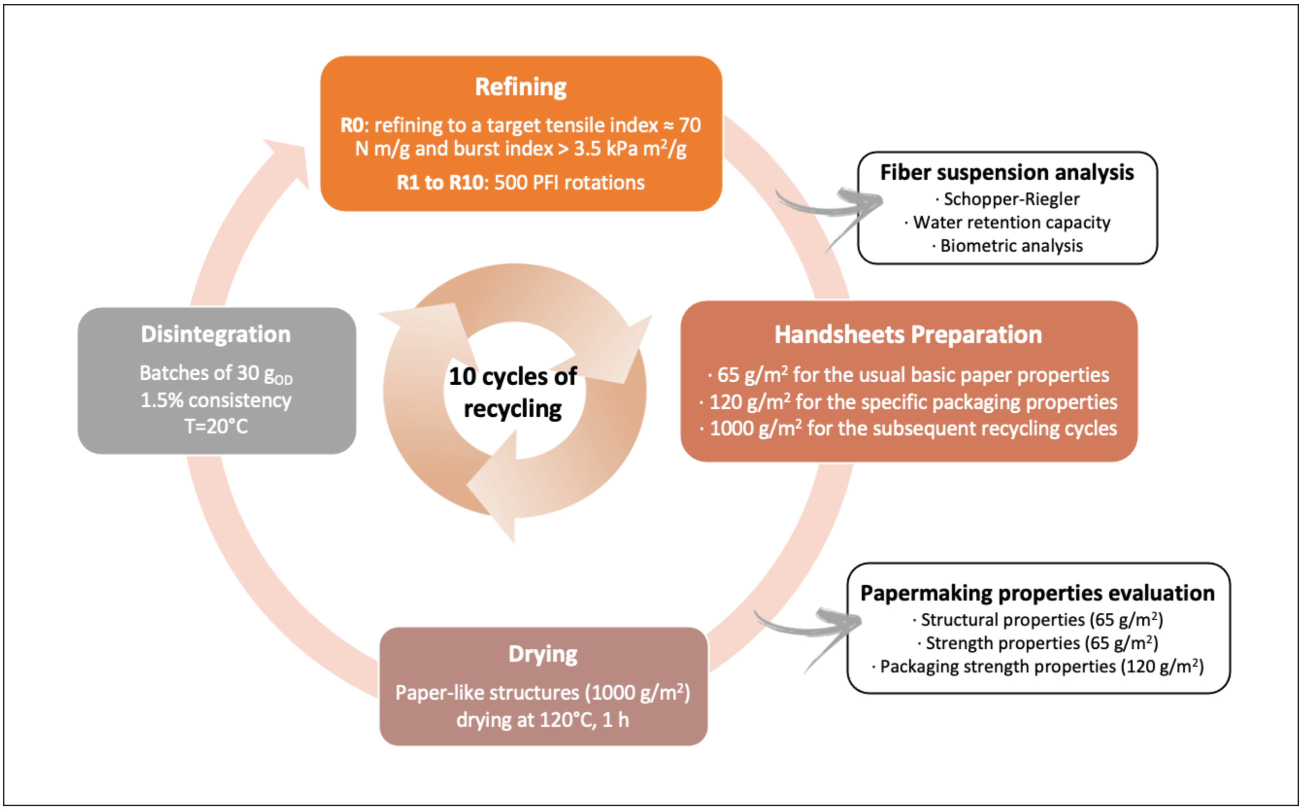
In this work, a comparative study of the performance of unbleached pulps from commercial bale sheets of dried short fiber (*Eucalyptus globulus* kraft pulp) and long fiber (*Pinus sylvestris* kraft pulp) during multiple recycling cycles is presented. The recycling methodology presented by Sousa et al. [17], which studied the recycling performance of different short hardwood fibers, is close to the industrial practice. So, the methodology adopted in the present work was the same proposed by Sousa et al. [17]. Structural, chemical, and mechanical properties of both fibers were analyzed; also, critical properties, such as short-span compression strength and corrugating medium resistance were tested in order to estimate the performance of these two types of fibers in paper and board applications.

EXPERIMENTAL

Two types of dried commercial chemical pulps were evaluated for this work: unbleached eucalyptus kraft pulp (UEKP) and unbleached softwood kraft pulp (USKP). The UEKP is produced from eucalyptus wood (about 95% *Eucalyptus globulus*), with a final kappa number of 14. The USKP is a commercial pulp produced from pine wood (about 80%–100% *Pinus sylvestris*), with a final kappa number between 80 and 90. Each pulp was refined in a PFI lab refiner according to ISO 5264-2 "Pulps—Laboratory beating—Part 2: PFI mill method" to a mill standard with a target tensile index of 70 N m/g and burst index above 3.5 kPa m^2/g and short span compression index above 17.5 N m/g (as required for a brown kraftliner paper); this is considered as recycling cycle 0 (R0). So, in the cycle R0, 900 g of each pulp (in batches of 30 g, ovendry [o.d.] weight) was disintegrated at 1.5% consistency. Then, the UEKP and USKP were PFI refined with 1190 and 1375 PFI rotations, respectively, according to the number of rotations pre-selected for the target tensile index. For the following recycling cycles R1 to R10, the refining treatment was the same for both pulps—a slight refining of 500 PFI rotations—in order to enhance some reinforcement capacity for these recycled fibers in the formation of recycled packaging papers. Fiber and paper characterization were performed on

Property	Standard	Test Name
Drainage	ISO 5267-1	Pulps—Determination of drainability
Water retention capacity (WRV)	SCAN-C 62:00	Chemical pulp—Water retention value
Grammage	ISO 536	Paper and board—Determination of grammage
Bulk	ISO 534	Paper and board—Determination of thickness, density and specific volume
Air resistance – Gurley	ISO 5636-5	Paper and board—Determination of air permeance
Burst index	ISO 2758	Paper—Determination of bursting strength
Tensile index	ISO 1924-2	Paper and board—Determination of tensile properties
Internal bond strength (Scott-bond)	TAPPI T 569 pm-00	Internal bond strength (Scott type)
Zero-span tensile strength	TAPPI T 231 TAPPI T 273	Zero-span breaking strength of pulp (dry zero-span tensile) Wet zero-span tensile strength of pulp
Short-span compression index (SCT)	ISO 9895	Paper and board—Compressive strength —Short-span test
Crush resistance of fluted medium index (CMT-30)	TAPPI T 809 om-99	Flat crush of corrugating medium

I. Analyzed properties and respective test methods



1. Recycling and testing procedure.

R0, R1, R2, R4, R6, R8, and R10 cycles. In each of these cycles, fiber suspension was analyzed for the Schopper-Riegler value; water retention value (WRV); hornification, which is measured as relative WRV reduction (WRV_{R0} -WRV_{Ri})/WRV_{R0} x100 (%), where i stands for the number of recycling cycles; and biometric characteristics with the FiberTester Model 912 equipment from Lorentzen & Wettre (Kista, Sweden). Microscopic analysis of the fiber cross section was also performed for each cycle with a Dialux 20 EB microscope from Leica (Wetzlar, Germany) for measuring the fiber external diameter (D_e) and lumen diameter (D_l) on about 100 fibers until constant standard deviation. The fiber wall thickness (ε) was calculated by $(D_e$-$D_l)/2$, and the Runkel coefficient was calculated according to the formula $2x\varepsilon/D_e$.

Around 30 g (o.d. weight) of each pulp sample were converted to laboratory isotropic round sheets with an air dry grammage of 65 g/m² according to ISO 5269-1 "Pulps—Preparation of laboratory sheets for physical testing—Part 1: Conventional sheet-former method." They were tested for the usual basic paper properties, such as bulk, air resistance, burst and tensile indexes, internal bond strength, and dry and wet zero-span tensile strength. Also, handsheets with an air-dry grammage of 120 g/m² were prepared using the same method for testing of the required packaging properties, such as burst index, short-span compression strength index (SCT), and crush resistance index (CMT-30). **Table I** lists all properties tested and their respective standard testing method.

In each cycle, the unused pulp from production of the 65 and 120 g/m² handsheets was converted to high grammage laboratory sheets (1000 g/m²) in a Rapid-Köthen former by adapting ISO 5269-2 "Pulps—Preparation of laboratory sheets for physical testing—Part 2: Rapid-Köthen method." Then, the handsheets were dried at 120°C for 1 h to simulate the papermaking process. These paper-like structures were used in the subsequent recycling cycle of disintegration, refining, handsheet preparation, and drying. This procedure was repeated several times, as **Fig. 1** shows.

Chemical and physical characterization of pulp fibers was performed on selected cycles (R0, R2, and R10). The extractives content was determined using an adaptation of the TAPPI Standard Test Method T 204 cm-97, "Solvent extractives of wood and pulp," by soxhlet extraction with 1:2 ethanol/toluene. The acid insoluble lignin was determined by Klason method according to TAPPI T 222-om 06 "Acid-insoluble lignin in wood and pulp." For determination of acid soluble lignin, TAPPI UM 250, "Acid-soluble lignin in wood and pulp" was adapted by adding a step with sodium borohydride ($NaBH_4$) in order to reduce interferences and measuring the absorbance at 280 nm [18]. For carbohydrate analysis, the method from Selvendran et al. [19], Blakeney et al. [20], and Oliveira et al. [21] was used. The volume of pores (macropores, mesopores, and micropores) per gram of fiber was obtained by thermoporosimetry analysis. This analysis was performed following the method described by Maloney [22] for cellulose samples; however, for UEKP and USKP, semicontinuous freezing of the samples between 0.2°C and -20°C was applied.

RESULTS AND DISCUSSION

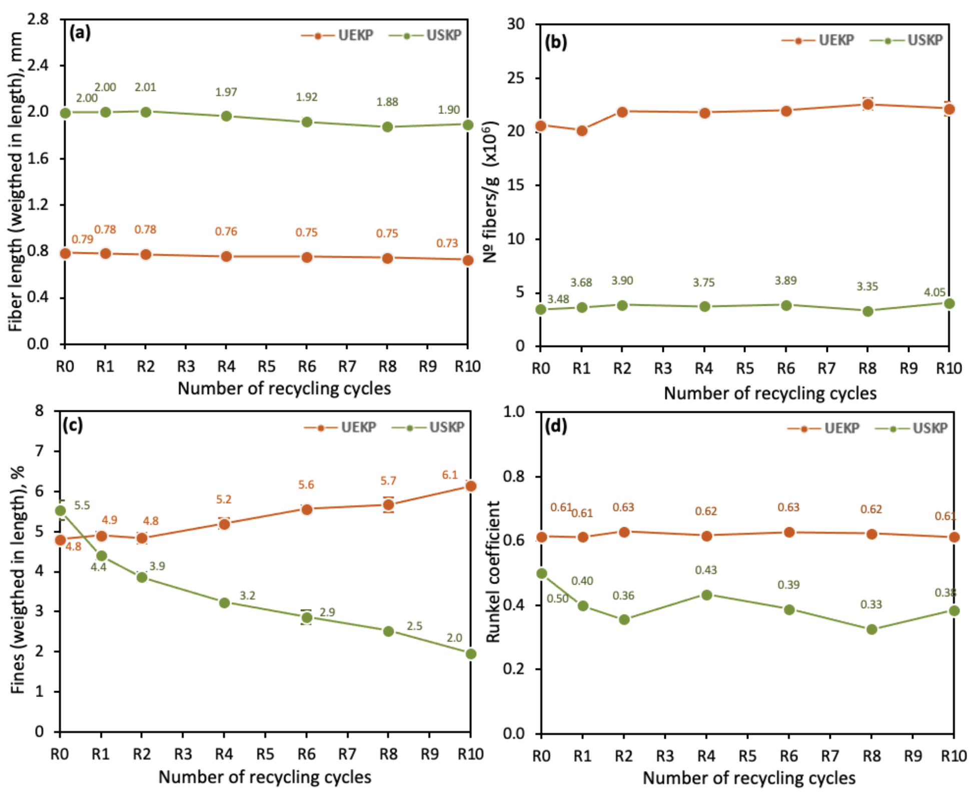
The biometric characteristics of the two virgin pulps before refining are described in **Table II**. As expected, the *Eucalyptus globulus* pulps are shorter and narrower and present lower coarseness, but they have a higher Runkel coefficient in comparison with the corresponding softwood kraft pulp. The higher Runkel coefficient of the *E. globulus* fibers provide a fiber with lower collapsibility, which provides the characteristic higher paper bulk to the paper material produced from this kind of fiber. For the purpose of this study, it is also important to highlight that the fines content of both pulps is similar.

Fiber Tester	UEKP	USKP
Fiber length (arithmetic), mm	0.672	1.400
Fiber length (weighted in length), mm	0.776	2.060
Fiber width, µm	17.5	34.8
Number of fibers/g x 10^{-6}	23.4	4.0
Coarseness, mg/100 m	6.4	17.9
Fines content (weighted in length), %	5.0	5.2
Optical microscope		
Fiber wall thickness, µm	4.0	7.3
Fiber external diameter, µm	15.1	43.1
Runkel coefficient	0.53	0.34

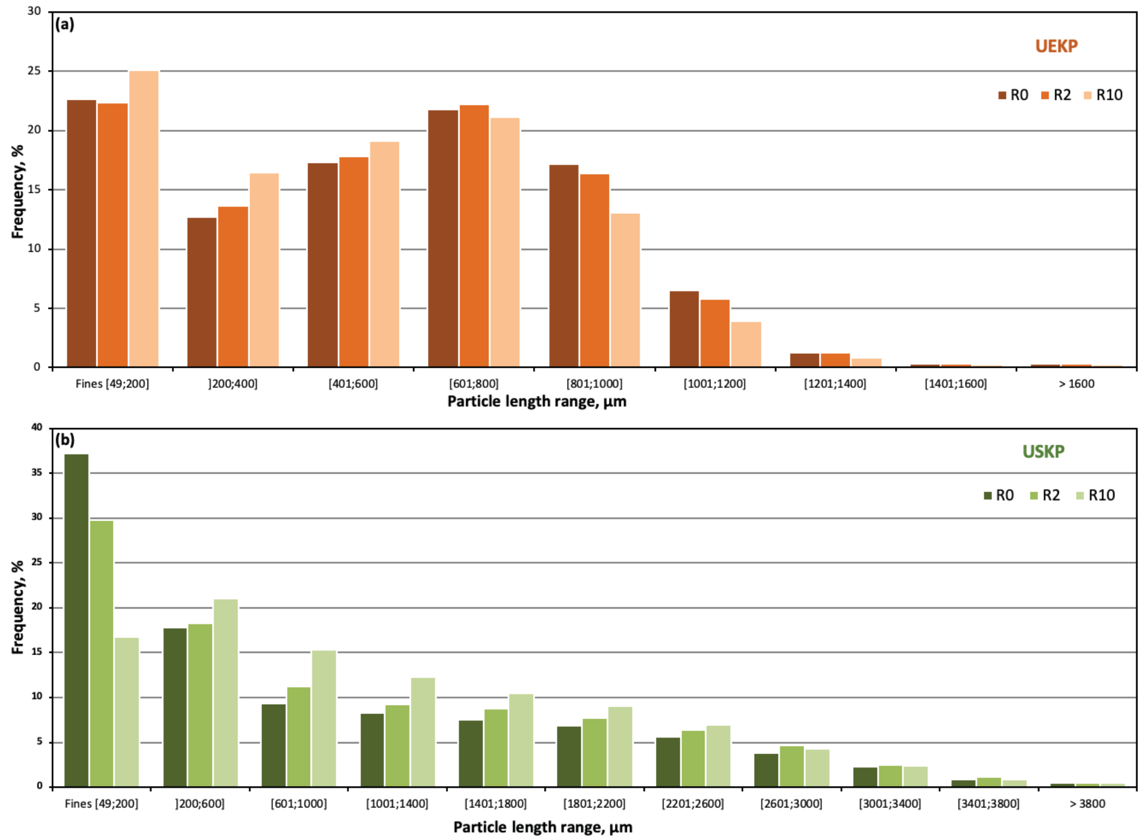
II. Morphological properties of the unbleached eucalyptus kraft pulp (UEKP) and unbleached softwood kraft pulp (USKP) virgin/primary fibers before refining.

Effect of recycling on fiber morphological properties

The effect of the recycling process on the fiber length (weighted in length) is very low for both pulps, in accordance with the data reported in literature [8]. The fiber length reduction was about 7% and 2%, respectively, for short and long fibers (**Fig. 2a**). The recycling cycles affect the different classes of fiber length, demonstrating the small increase of short fiber classes at the expense of the long fiber classes, particularly for the 10th recycling cycle (**Fig. 3**). The number of fibers per gram increase with recycling (8% for UEKP and 16% for USKP) (Fig. 1b), in agreement with increased population of short fibers (Fig. 3).



2. Effect of recycling on (a) average fiber length, (b) number of fibers per gram, (c) fine elements content, and (d) Runkel coefficient of the unbleached eucalyptus kraft pulp (UEKP) and the unbleached softwood kraft pulp (USKP).

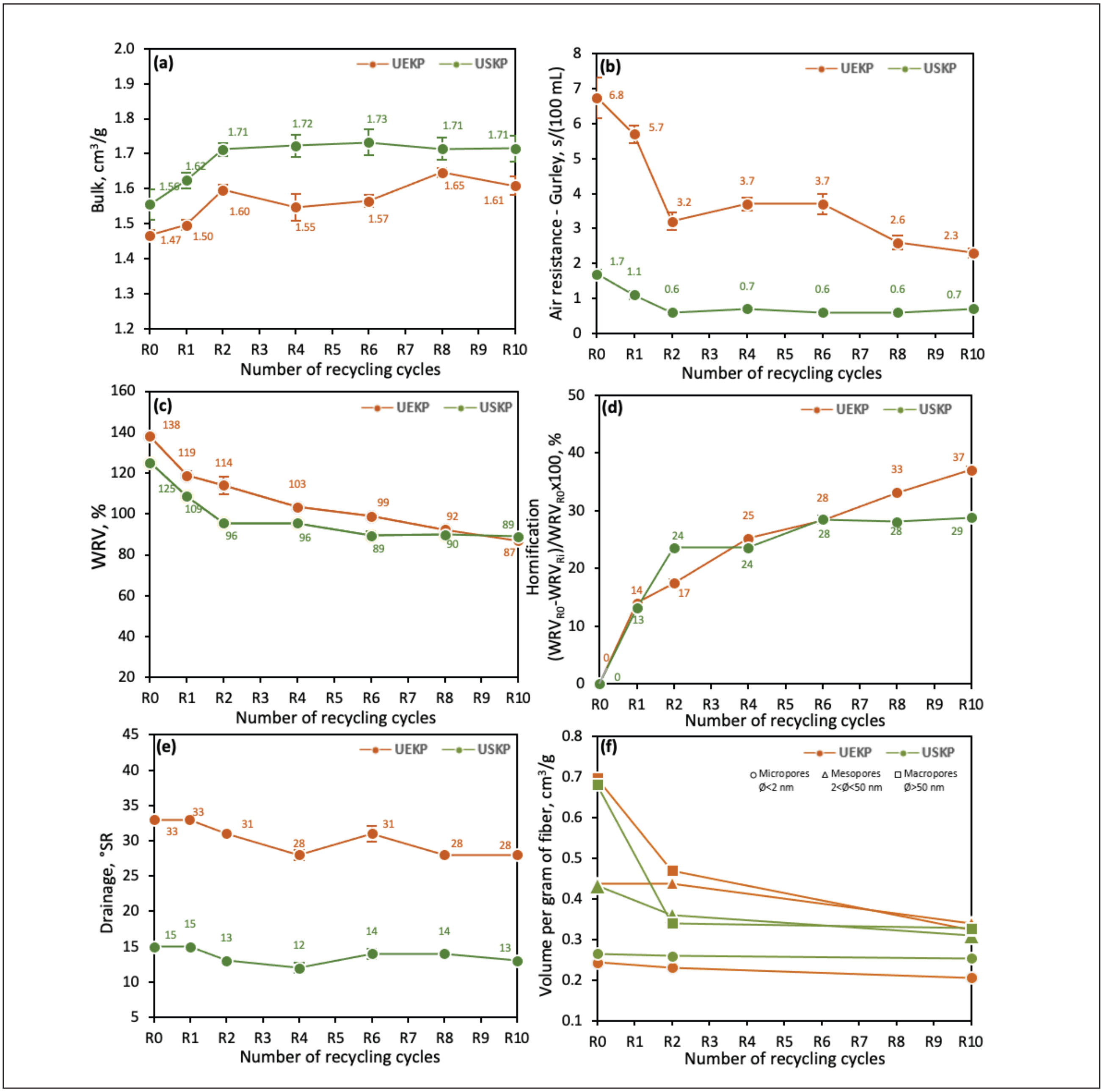


3. Effect of recycling on different ranges of fines and fibers frequency for (a) UEKP and (b) USKP (cycles R0, R2, and R10).

Regarding the behavior of the fine elements pulp content during recycling, the UEKP exhibited the expected increase in fines content with recycling—a consequence of the pulp drying, pulp disintegration, and the slight refining operation (500 PFI rotations) between cycles, and it is in agreement with most of the results in literature [8]. On the contrary, the fines content for USKP consistently decreased with recycling (Fig. 2c), which is, at first glance, an unexpected result. This is probably due to the negative balance between the fines generation by the above cited unit operation and the loss of fines in both paper-like structure formation (1000 g/m²) and normal sheet drainage. In fact, experimental assays confirmed significant fines loss during the paper-like structure formation (1000 g/m²) in the Rapid-Köthen handsheet former, which was used to recover the non-used pulp in each cycle, for USKP. The open structure formed by the long fibers and the applied vacuum pressure (270 mbar) provide the conditions for fines loss, particularly for the softwood pulp fibers.

Effect of recycling on pulp sheet structural properties

Due to the positive effect of fiber length on pulp handsheet mechanical properties, the softwood pulp handsheet presents a lower apparent density (higher bulk) than the short fibers to reach the tensile index criterion of 70 N m/g. The burst strength of the USKP is higher than for the UEKP (5.50 kPa m²/g vs. 4.58 kPa m²/g). The evolution of the pulp handsheet bulk with recycling is illustrated in **Fig. 4a** and shows that the most important effect for both pulps occurs in the first two cycles. For UEKP, after the initial increase in bulk, a slight decrease followed by a final increase of bulk took place. The bulk profile reflects the strong contribution of fiber hornification and probably some contribution of the fine elements content. For UEKP, the fines content remains practically unchanged for R0–R2 (Fig. 4c), and the drastic increase of bulk should reflect the drastic increase in fiber hornification. After this stage, the increase in fines content might counteract the additional hornification and lead to a slight increase in structure densification (lower bulk index). The air-permeability profiles are in line with the bulk density variation (Fig. 4b). The bulk density of the USKP increased drastically from R0 to R2 and remains practically unchanged thereafter. Interestingly, the same profile was observed for the USKP water retention values along the recycling cycles, suggesting a non-significant change in hornification after the R2 cycle (if the continued decrease in the fines elements content is considered,



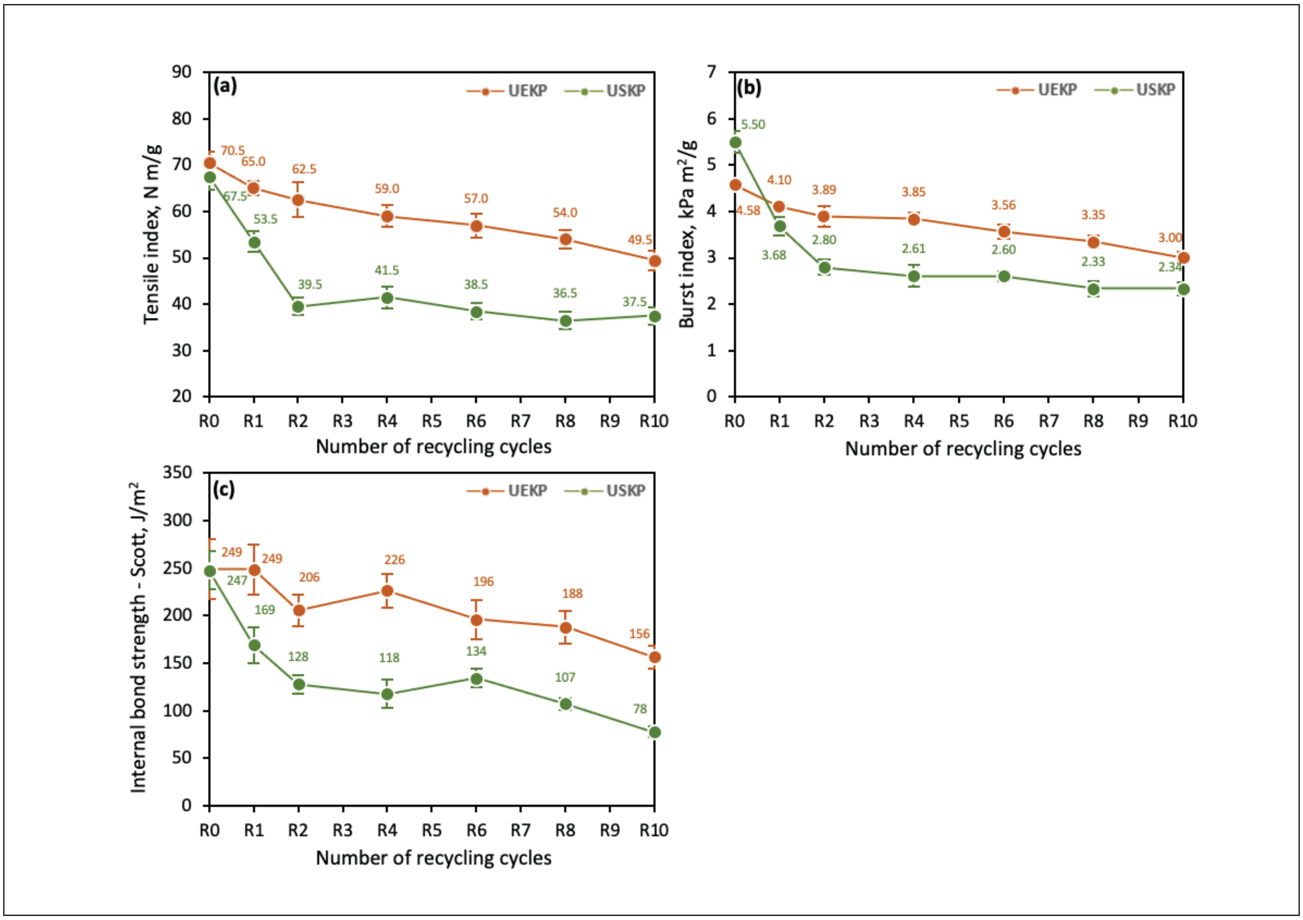
4. Effect of recycling on structural properties of UEKP and USKP handsheets: (a) bulk, (b) air resistance, (c) water retention capacity, (d) hornification, (e) drainage resistance, and (f) pore volume per gram of fiber.

the data may suggest some marginal increase in fiber flexibility to compensate the fines content decrease). On the contrary, the UEKP exhibits a more gradual hornification along the recycling cycles, as measured by the WRV (Fig. 4c and Fig. 4d). Figure 4f confirms that the loss of pores is less drastic for UEKP than USKP in the initial recycling cycles.

As shown in Fig. 4e, drainage resistance decreased about 15% (from 33°SR to 28°SR) for UEKP, despite about a 27% increase in fines elements, putting in evidence the fiber hornification. The suspension drainage resistance of softwood fibers also decreases about 13%, from 15°SR to 13°SR, but a fines elements content reduction from 5.5% to about 2% was also observed.

Effect of recycling on pulp sheet mechanical properties

Figures 5a–5b show the profile of the tensile and burst indexes for both pulps along the recycling, where we can appreciate the higher recycling sensitivity of the softwood fibers in comparison with the hardwood fibers. The decrease in tensile index between the R0 and R10 is about 30% and 46% for UEKP and USKP, respectively. The corresponding values for the burst index follow the same

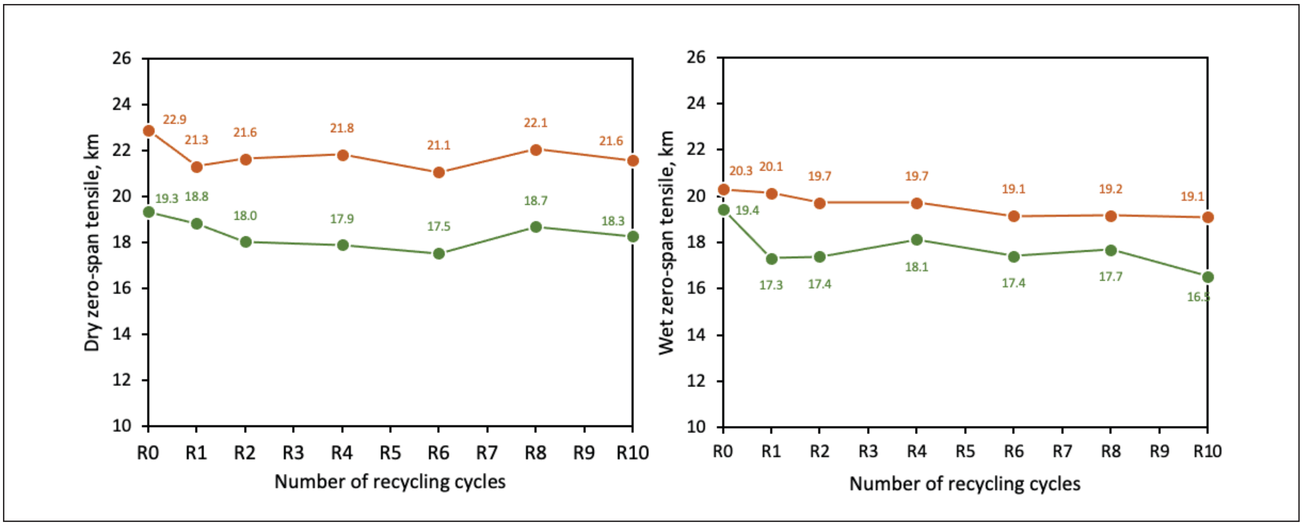


5. Effect of recycling on (a) tensile strength, (b) burst strength, and (c) internal bond strength of UEKP and USKP handsheets.

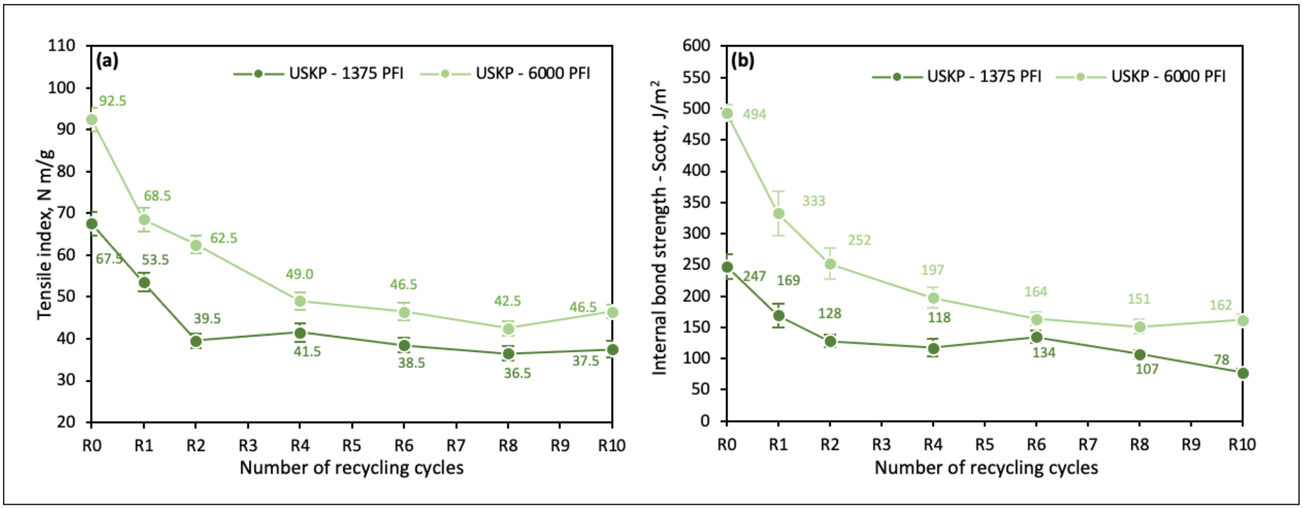
trend, decreasing 36% and 57%, respectively, for UEKP and USKP. Moreover, whereas the decrease of these properties is gradual along the recycling for *E. globulus*, on the contrary, the decrease practically occurs all of the first two cycles for the softwood fibers, in accordance with the WRV profile.

The reasons behind this drastic decline can tentatively be due to: the lower intrinsic fiber strength; the poor external fibrillation of the softwood pulp due to the low initial beating and corresponding lower apparent density; fines elements loss; and other physic-chemical characteristics of these softwood fibers. The dry and wet zero-span tensile indexes (**Fig. 6**) clearly indicate that the intrinsic fiber resistance is not the limiting factor in the mechanical performance, despite the slightly lower intrinsic fiber strength of USKP. To further investigate the eventual role of the external fibrillation and the low softwood pulp handsheet density and possible corresponding low mechanical properties, more refining energy was applied to the same original USKP (6000 PFI rotations) to obtain the highest mechanical performance of this pulp. **Figure 7a** compares the tensile index evolution for the softwood pulp refined at 1375 PFI and 6000 PFI rotations. Despite the much higher initial handsheet pulp density (0.82 g/cm³ vs. 0.63 g/cm³) and the increase of the initial tensile index value from 67.5 N m/g to 92.5 N m/g, the tensile index loss (between R0 and R4) was 47% and 38% for the USKP initially refined at 6000 PFI and 1375 PFI rotations, respectively. The corresponding losses of the internal cohesion were 60% and 52%, respectively (Fig. 7b). The UEKP tensile loss was only 16% between R0 and R4. It should be emphasized, however, that the high beating level imposed on the softwood pulp is not to be applied in real conditions. Using as reference the same R0 and R4 recycling cycles, the burst index of this softwood fiber decreases 50% and 53% for the 6000 PFI and 1375 PFI treatment, respectively, and the corresponding burst index loss for the *E. globulus* fiber is only about 16%. These results indicate that the relative loss of mechanical performance of the USKP is not determined by the refining level or the handsheet density in the studied range (**Fig. 8**). So, the results strongly suggest that both the high tensile loss and internal bond strength loss with recycling for this softwood fiber is an intrinsic characteristic of this pulp.

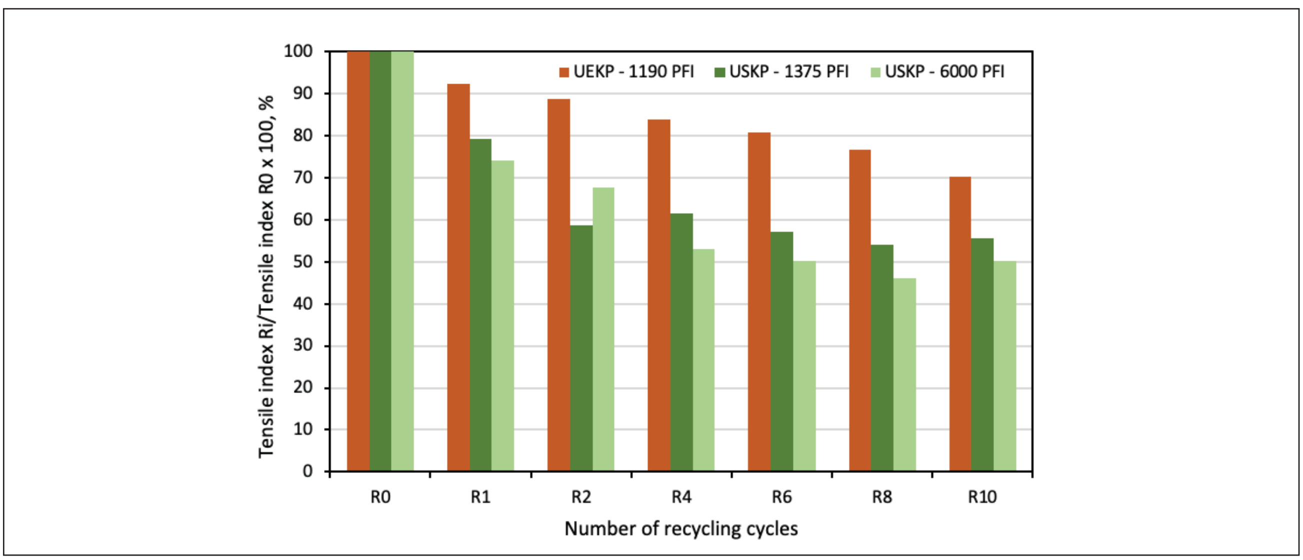
In conclusion, the reason behind the higher mechanical resistance loss of this softwood fiber with recycling is probably the physic-chemical surface and/or ultrastructural fiber wall characteristics that induce a drastic decrease in inter-



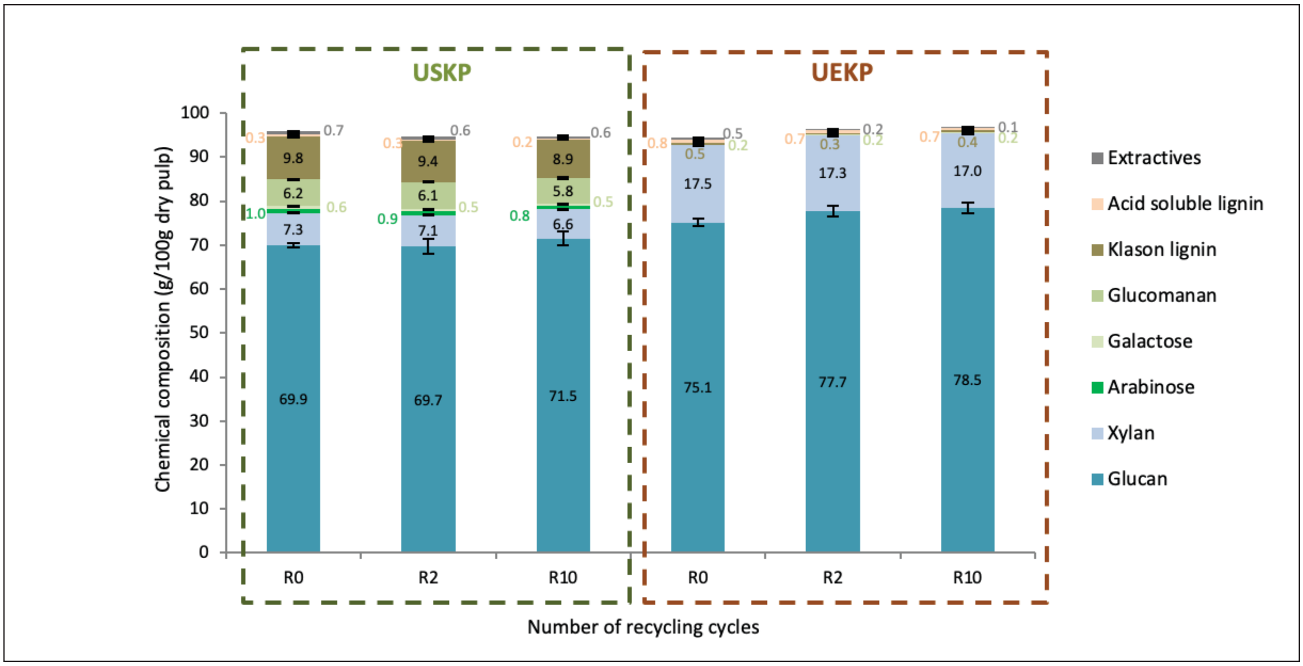
6. Effect of recycling on zero-span tensile, dry and wet, of UEKP and USKP handsheets.



7. Effect of recycling on (a) tensile index and (b) internal bond strength of USKP handsheets with two levels of initial beating (1375 PFI rotations and 6000 PFI rotations).



8. Relative tensile index loss for UEKP and USKP refined at 1375 PFI and 6000 PFI rotations.



9. Evolution of hemicelluloses, lignin, and extractives content on USKP and UEKP (recycling cycles R0, R2 and R10).

fiber bond potential with recycling (Fig. 5c). This may be due to the irreversible fibrils' collapse onto the fiber surface, with fibril element rearrangement due to the thermal softening, as was proposed by Hubbe et al. [5]. The high lignin content of the USKP (10.1%), compared with the UEKP (1.3%), can promote the thermal softening of the fibrils when the pulp was wet dried in the recovery process between recycling cycles, impairing the interfiber bonding. The hemicellulose composition of UEKP and USKP is different, as expected (**Fig. 9**). The UEKP initially has a slightly higher hemicellulose content, which is in accordance with the higher WRV of this pulp. On the other hand, the small decrease of hemicellulose content observed for both pulps with recycling does not justify the strong reduction in the WRV with recycling, demonstrating again the role of fiber hornification.

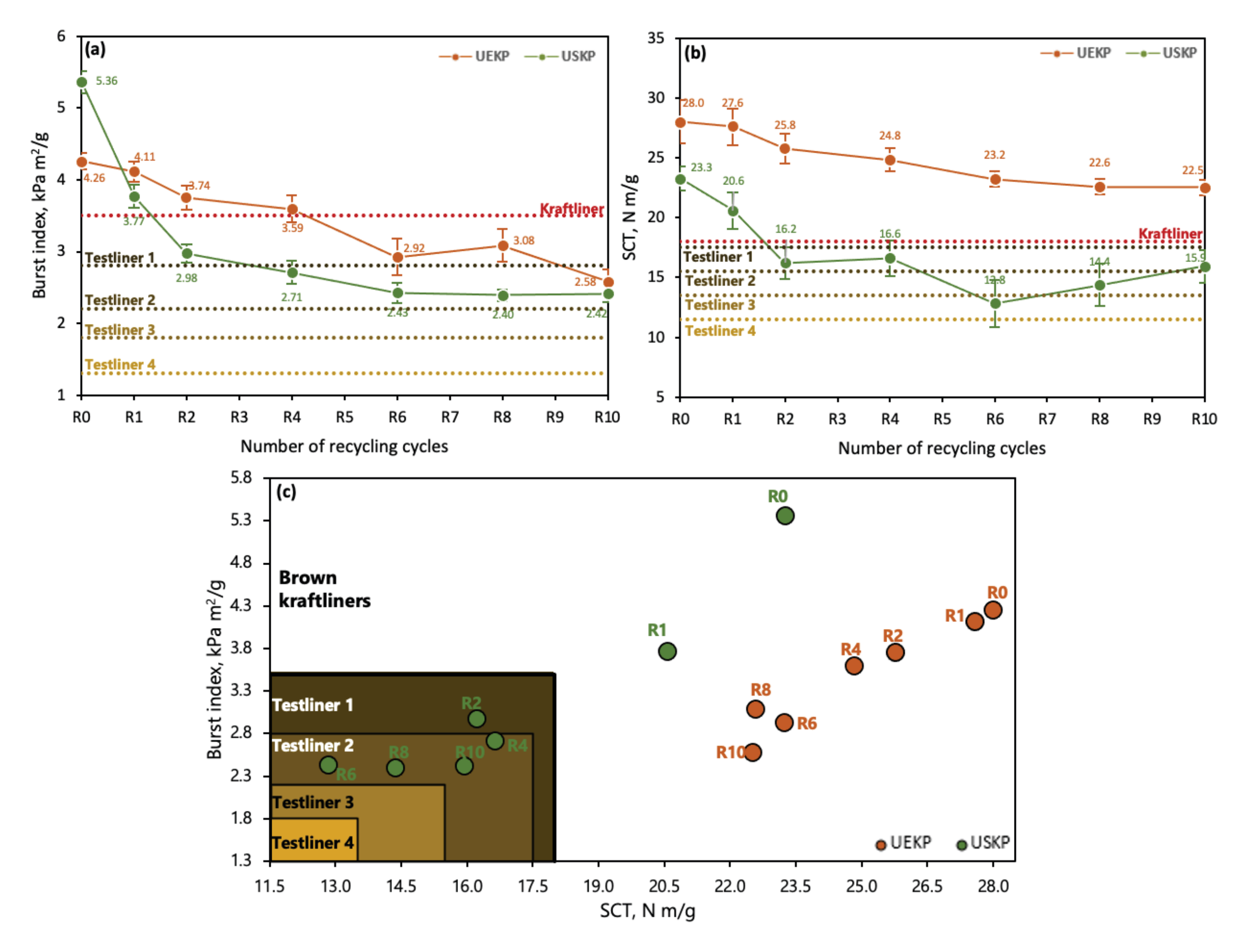
Packaging functional properties

To further explore the potential of these two pulps for packaging papers, handsheets of 120 g/m² were produced and analyzed in terms of burst index, SCT index, and crush resistance of fluted medium (CMT-30). The first two parameters are considered as important strength properties for liners, as they are a good indicator of strength performance of a box, flexibility during converting, and use of the corrugated board. Burst index and short-span compression test, cross-machine direction (SCT-CD) index determine the classification of the papers regarding their potential as brown kraftliner or brown testliner grades; requirements for these parameters of paper grammage, including 120 g/m² and according to the Confederation of European Paper Industries (CEPI), are shown in **Table III**.

Grade	Burst Index or SCT-CD Index	
	ISO 2758, kPa m²/g	ISO 9895, N m/g
Brown kraftliner (< 250 g/m²)	≥ 3.5	≥ 18.0
Testliner 1 (< 200 g/m²)	≥ 2.8	≥ 17.5
Testliner 2 (< 200 g/m²)	≥ 2.2	≥ 15.5
Testliner 3 (≥ 120 g/m²)	≥ 1.8	≥ 13.5
Testliner 4 (≥ 90 g/m²)	≥ 1.3	≥ 11.5
SCT-CD: short-span compression test, cross-machine direction index.		

III. The CEPI requirements for linerboard grades (brown kraftliner and brown testliners) for paper grammage, including 120 g/m² [14].

Figure 10 shows the higher performance of the UEKP compared with USKP. Considering CEPI criteria for the brown kraftliner grade (Fig. 10c), UEKP pulp fulfills the grade range values for all the recycling cycles tested, whereas USKP loses that rating in the second recycling cycle. As expected, the profile of the burst index with recycling for the 120 g/m² handsheets is similar to those observed for the handsheets of 65 g/m² (Fig. 5b). The experimental values obtained for the SCT index (Fig. 10b) revealed the high performance of the UEKP structures, with values much higher than those required for brown kraftliner throughout the 10 recycling cycles. Even for R0, the SCT value of USKP handsheets is lower than the UEKP, despite the superior burst index and similar internal bond strength and tensile



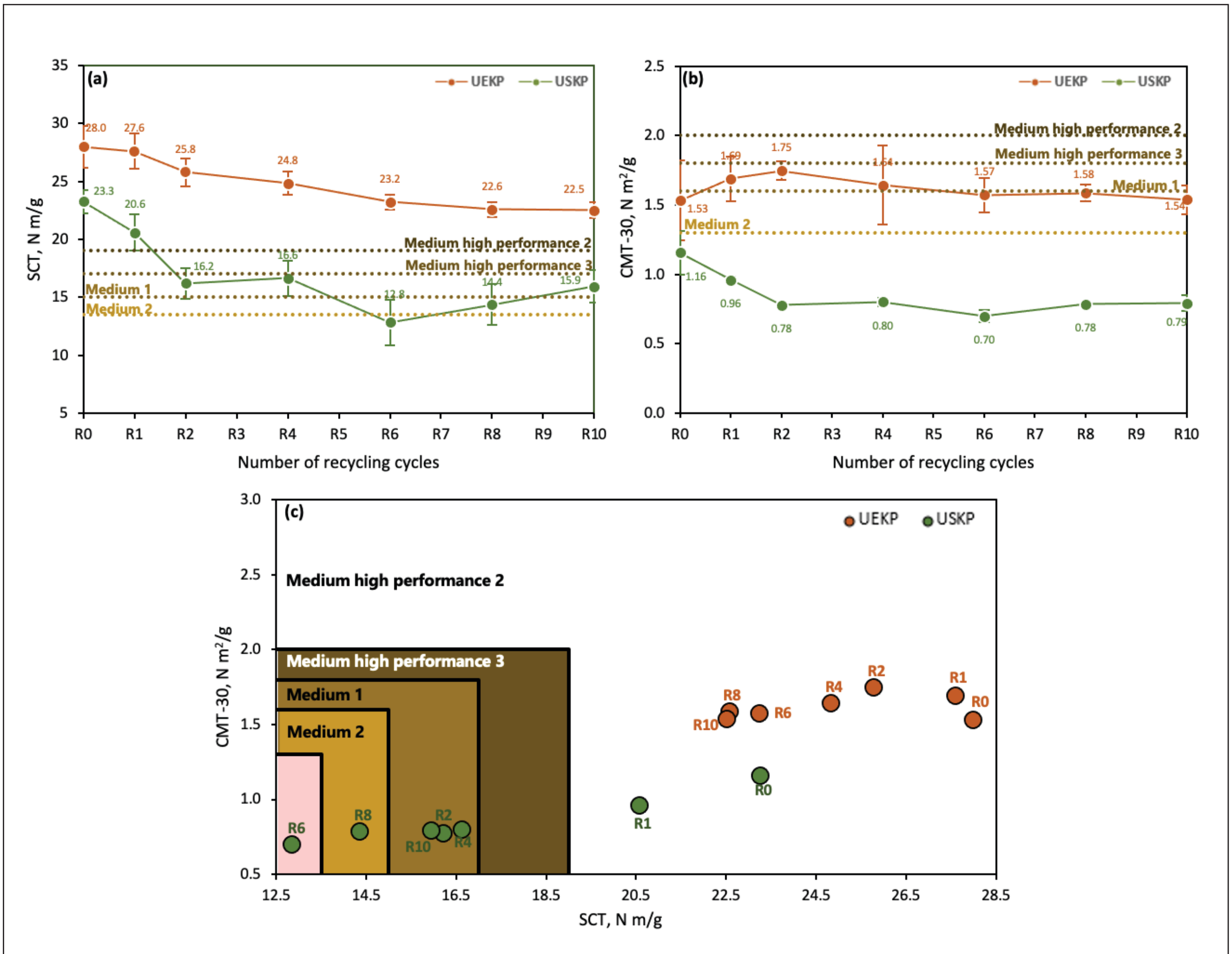
10. Effect of recycling on (a) burst and (b) SCT indexes of UEKP and USKP handsheets (120 g/m²), and (c) rating of UEKP and USKP handsheets on each recycling cycle for liner grades, according to CEPI requirements [14].

index. For a moderately consolidated fiber network, the in-plane compressive strength depends on the interfiber bond and on the compression strength of the fibers [23]. A Scott-bond tester measures the delamination energy, which has a strong contribution to interfiber bond, but fiber breaking or pull-out can also play a role, and therefore it is not certain whether the interfiber bond is similar in UEKP and USKP. If so, it can be speculated that the softwood pulp fibers may have lower compression strength.

The higher collapsibility of the softwood pulp fibers, anticipated by the lower Runkel coefficient (Fig. 2d), can lead to an easier buckling of the fibers and structure failure. The relative importance of interfiber bond, including the length of unbonded fiber segments and fiber compression strength, deserves further investigation. However, the drastic decrease of SCT index in USKP handsheets with recycling seems to be related to the drastic decrease of the internal bond strength (Fig. 5c). Although a part of this decrease can be attributed to the loss of fines, other specific characteristics of this softwood fiber play a major role.

On the other hand, the short-span compression index (SCT) and crush resistance of fluted medium (CMT-30) determine the classification of these papers regarding their potential as recycled fluting grades. The CEPI requirements for these parameters for paper grammage above 100 g/m² are shown in **Table IV**.

The excellent performance of the UEKP was revealed again with higher crush resistance throughout the ten recycling cycles when compared with USKP (Fig. 11b). Considering only the CMT-30 parameter, USKP did not comply with recycled fluting requirements, while UEKP showed performance in medium 1 and 2 fluting grades. Figure 11c shows that UEKP stays on the high performance recycled fluting grade for all the ten cycles once that SCT is over 19.0 N m/g, while the USKP loses performance in medium 1 and 2 grades after two cycles. To further investigate the potential of the softwood pulp, handsheets of 120 g/m² were produced from the strongly refined (6000 PFI rotations) pulp. Despite the much higher density (about 19% more), tensile index and internal bond (Fig. 7) of these handsheets when compared with the UEKP (1190 PFI rotations), the initial CMT-30 index (R0) is of the same magnitude (**Fig. 12**). So, taking into account



11. Effect of recycling on (a) SCT and (b) CMT-30 indexes of UEKP and USKP handsheets (120 g/m²), and (c) rating of UEKP and USKP handsheets on each recycling cycle for recycled fluting grades, according to CEPI requirements [14].

Grade	SCT-CD Index or CMT-30 Index	
	ISO 9895, N m/g	ISO 7263, N m²/g
Medium high-performance 2	≥ 19.0	≥ 2.0
Medium high-performance 3	≥ 17.0	≥ 1.8
Medium 1	≥ 15.0	≥ 1.6
Medium 2	≥ 13.5	≥ 1.3

SCT-CD: short-span compression test, cross-machine direction index. CMT-30: crush resistance index.

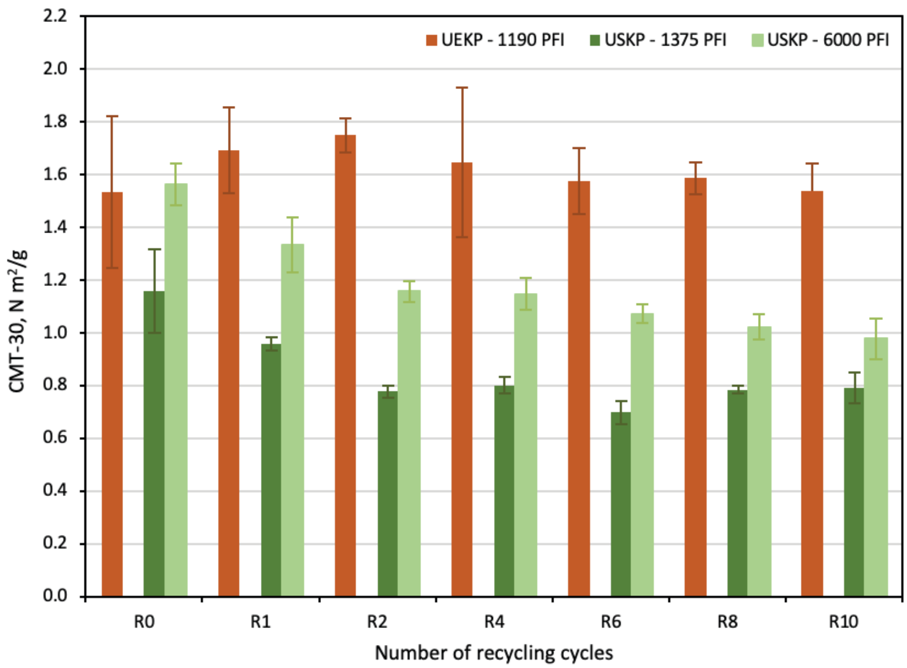
IV. The CEPI requirements for recycled fluting grades (≥ 100 g/m²) [14].

the much higher internal bond of the USKP (6000 PFI rotations) compared with the UEKP (1190 PFI rotations), the results strongly suggest that these softwood fibers are less rigid, leading to easier buckling and premature collapse of the structure. Moreover, for the R0 cycle, the fines content is similar in both pulps. With recycling, the CMT-30 values of the USKP degrade drastically due to the internal bond decrease. On the contrary, the values of CMT-30 for the UEKP remain at very high levels, despite the small decrease of internal bond along the recycling. These results are in accordance with those presented by Whitsitt and Sprague [24], who reported fiber bonding as the major factor affecting compressive strength. Therefore, well-bonded stiff and thick fibers, such as the UEKP evaluated in this study, are the most suitable for increasing the recyclability of the paper, without compromising the packaging functional properties.

CONCLUSIONS

A comparative study of the recycling potential of unbleached eucalyptus kraft pulp (UEKP) and unbleached softwood kraft pulp (USKP) was carried out starting with the same initial tensile index of 70 N m/g. The main conclusions are as follows:

- The effect of recycling on the fiber length (length weighted and number weight) was low for both pulps; a small increase on the short fiber class took place at the expense of the long fiber one.



12. Effect of recycling on CMT-30 index of UEKP handsheets and USKP handsheets with two levels of initial beating (1375 PFI rotations and 6000 PFI rotations).

- The initial water retention value of the UEKP fibers was about 10% higher than the corresponding values for USKP, in accordance with the higher hemicellulose content and lower lignin content of the UEKP.
- The bulk of the handsheets increased about 10% in the two initial recycling cycles for both pulps and remained roughly at the same level thereafter; USKP presented a higher bulk than UEKP.
- The tensile and burst indexes and internal bond strength of the USKP decreased more drastically with recycling than the UEKP. Although a part of this difference can be ascribed to the higher fines loss during recycling of the softwood fibers compared to the UEKP, the majority can be attributed to more severe irreversible collapse of fibrils on the fiber wall, which was eventually enhanced by the thermal softening of surface lignin in fibers.
- Due to the moderate decrease of burst index, crushing resistance index, and mainly short-span compression index, the UEKP preserved the requirements for brown kraftliner and for high performance recycled fluting grades during all the ten recycling cycles, whereas the USKP lost this rating after the second cycle. **TJ**

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Demand for packaging papers is growing, and consequently, so is the demand for raw materials with the required specifications, even after several recycling cycles. The study of the fiber resistance towards recycling on a comparative basis helps support decisions about fiber sources and processing.

In the literature, evaluation of pulp recycling potential has been mainly focused on softwood pulp through analysis of typical papermaking properties and using conditions far from those applied in an industrial recycling process. In this work, the recycling methodology is close to industrial practice, and critical properties for packaging papers were analyzed for both softwood and hardwood fibers.

The most difficult aspect of this study was the extensive work required to get all the recycling cycles done in the laboratory in a short timeframe. Very good and rigorous planning and collaboration between the authors was the way to overcome this challenge and to reach to good quality results.

We discovered the high relevance of fiber type on papermaking properties from the perspective of packaging papers through this study. Our most interesting finding was the outstanding behavior of the UEKP, which addressed the requirements for brown kraftliner and for high performance recycled fluting grades during all the ten recycling cycles.

Considering the growing demand for packaging papers, as well as the global momentum for a circular economy, the information in this study will provide data for mill selection of raw materials and for anticipating the impact of multiple recycling cycles on paper properties. Our next step is to evaluate other pulp types using a similar recycling study.

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