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Microcrystalline cellulose: an alternative to increase the resistance of kraft packaging with recycled fiber

Celulose microcristalina: uma alternativa para aumentar a resistência de embalagens kraft com fibra reciclada

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ABSTRACT

The consumption of paper packaging is increasing. On the contrary, the planted areas of *Pinus spp.* are showing a trend tendency of imbalance between supply and demand. Therefore, many companies are prioritizing the use of recycled fiber (RF). However, its inclusion can influence the quality of the product. This study aimed to evaluate whether the combination of RF with microscale cellulose will enable the production of resistant paper. The first step involved producing bench-scale samples of Kraft paper (with different percentages of virgin and RF) and characterized it physically (grammage, moisture, Gurley porosity, Z-traction, SCT, and Mullen). The second stage involved replicating the first stage with the inclusion of microcrystalline cellulose (MCC) and the elimination of *Pinus spp.* (LF). All formulations were approved for the physical characterization tests, except for the porosity analysis and grammage for F5. In the first test (MCC=0%), there was a reduction in tensile, compression, and burst index of 13.2, 7.3, and 19.5%, respectively, showing that the higher the percentage of RF, the lower the paper's strength. In the second test for Formulation 3 (MCC=6%), there was an increase in the tensile, compression, and burst index of 9.5, 2.6, and 2.7%, respectively, when compared with Formulation 2 (LF=MCC=0%). This study demonstrates that the addition of up to 6% MCC strengthens the RFs and decreases the dependence on *Pinus spp.*, making it a promising alternative for the production of sustainable and resistant packaging.

Keywords: sustainable packaging; product development; mechanical properties; *Pinus spp.*

RESUMO

O consumo de embalagens de papel está aumentando; em contrapartida, as áreas plantadas de *Pinus spp*. apresentam tendência de desiquilíbrio entre oferta e demanda. Por isso, muitas empresas estão priorizando a utilização de fibra reciclada; contudo, a sua inclusão pode influenciar a qualidade do produto. O presente estudo teve como objetivo avaliar se a combinação de fibra reciclada com celulose em microescala permitiria a formação de papel mais resistente. A primeira etapa consistiu em produzir em escala de bancada amostras de papel Kraft (com diferentes porcentagens de fibra virgem e reciclada) e caracterizou-o fisicamente (gramatura, umidade, porosidade Gurley, tração Z, SCT e Mullen). A segunda etapa consistiu em reproduzir a primeira etapa com a inclusão da celulose microcristalina (MCC) e eliminação de *Pinus spp*. (FL). Todas as formulações foram aprovadas na caracterização física, com exceção da análise de porosidade e gramatura para F5. No primeiro teste (MCC=0%) houve redução no índice de tração, compressão e estouro de 13,2, 7,3 e 19,5%, respectivamente, demonstrando que quanto maior a porcentagem de fibra reciclada menor é a resistência do papel. No segundo teste para Formulação 3 (MCC=6%) houve aumento no índice de tração, compressão e estouro de 9,5, 2,6 e 2,7%, respectivamente, quando comparado à Formulação 2 (FL=MCC=0%). Este estudo demonstra que a adição de até 6% de MCC fortalece as fibras recicladas e diminui a dependência de *Pinus spp.*, em uma alternativa promissora para a produção de embalagens sustentáveis e resistentes.

Palavras-chave: embalagens sustentáveis; desenvolvimento de produto; propriedades mecânicas; *Pinus spp*.

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Introduction

In November 2022, the Earth reached a population milestone of eight billion people. Providing food, clothing, healthcare, safety, and comfort for all these individuals requires a complex system of production, storage, and logistics for goods and services. Furthermore, historical events and access to information are driving a shift in societal habits. During the COVID-19 pandemic, for instance, due to the need for remote shopping, the daily volumes of transported goods increased rapidly (Unnikrishnan and Figliozzi, 2021; German et al., 2022) and continued to grow post-pandemic as the population gained more confidence in online payment systems and experienced the convenience and ease of e-commerce. This fact is evident in the macroeconomic study conducted by FGV on the Brazilian packaging industry, with data showing a growth of 22.3% in 2020 compared with 2019, and the progress continued in 2021, with an increase of 31.1% compared with 2020 (ABRE, 2022). Another behavioral change among consumers is related to their concern about the environmental impacts of their actions and choices. Increasingly, society is reaching a consensus that everyone is responsible for preserving the environment, a responsibility that was previously attributed only to the public and private sectors. As a result, companies that align their environmental, social, and governance (ESG) actions with the United Nations Sustainable Development Goals (SDGs) stand out in the market (Didone et al., 2017; Zhang et al., 2022).

In an attempt to meet these new demands, different types of materials are being considered for packaging production according to their applicability. For many years, plastic stood out as a raw material for packaging production due to properties such as durability, low cost, better food preservation, and protection. However, there is a global trend toward the implementation of laws restricting the use of plastic items due to their long decomposition time and potential environmental pollution, posing a threat to aquatic animals (Horejs, 2020; Macleod et al., 2021). In this context, companies in the industry have been seeking alternative solutions. Cellulose, the main component of plant cell walls, is an attractive option for use as a raw material in packaging due to its renewability, recyclability, sustainability, and biodegradability (Didone et al., 2017; Didone and Tosello, 2019). This shift is already evident in the macroeconomic study conducted by FGV. In 2020, the plastic packaging segment was responsible for 36.0% of the total gross production value of the Brazilian packaging industry, and it decreased to 33.6% in 2022. In contrast, the segments of paper, corrugated cardboard, cartonboard, and paperboard showed growth in their shares, increasing from 31.6% in 2020 to 34.0% in 2022 (ABRE, 2022).

The sector responsible for the highest wood consumption in the world is the pulp and paper industry (FAO, 2021; Jochem et al., 2021). In Brazil, this sector uses 36% of the total planted areas and is the largest consumer of *Eucalyptus spp.* (short fiber — SF) and *Pinus spp.* (long fiber — LF) (IBÁ, 2022). Many companies seek certification processes, such as the Forest Stewardship Council (FSC), to demonstrate that their products and services are the result of environmentally sound forest management practices that are socially beneficial and economically viable (FSC, 2015; Galati et al., 2017). However, wood availability is directly affected by the amount of land allocated for planting, consumption, and recycling of products derived from this material. Meanwhile, the dependence on climatic conditions and forest management is taking a back seat (Lauri et al., 2021). The reduction of reforestation areas is already a reality in Brazil. In the state of Santa Catarina, for example, some areas that were once used for *Pinus spp.* planting have been replaced by soybean, corn, and pasture cultivation. As a result, the silviculture area has decreased by 723,000 hectares in 5 years, and there is now concern about a potential shortage of raw materials in the industrial sector (Ceron, 2021).

The increase in packaging consumption and the reduction in raw material availability justify, on their own, the search for alternative sources for paper production. In this regard, the use of recycled fiber (RF) is increasingly encouraged. In 2018, it is estimated that 230 million metric tons of paper were collected worldwide (FAO, 2021). In 2021, approximately 50% of recycled paper was used in the production of new cardboard boxes (World Economic Forum, 2022). Despite recycling being a promising alternative, paper cannot be recycled infinitely because the process causes fiber wear and losses. Therefore, the sustainable production of paper packaging relies on the proper proportion of RFs with virgin fibers sourced from forested areas. However, the significant challenge is to maintain the physical attributes and quality of the product (Hubbe et al., 2007; Zhang et al., 2022).

To ensure the integrity of the product, packaging needs to withstand applied force and impact, exhibit low gas permeability, and be minimally affected by temperature and ambient humidity (D'Almeida, 1988; Nechita and Roman, 2020). One alternative to increase paper strength is to utilize cellulose at the microscale and nanoscale due to its physical properties. Smaller structural elements result in larger surface areas, facilitating strong bonds and the formation of a robust fibrous network, which tends to increase paper density and strength (Klemm et al., 2011; Sharma et al., 2020). Microcrystalline cellulose (MCC) originates from any cellulose material that has had its amorphous fractions removed through treatment with dilute acids or enzymes. The result is a purified material with a predominant presence of crystalline regions, consisting of porous particles at the colloidal size range, which aggregate to form particles between 20 and 300 μm in diameter (Merci et al., 2015; Fouad et al., 2020).

In this scenario, the objective of this study was to replace virgin fiber from *Pinus spp.* with RF and MCC for the development of more sustainable and resilient packaging, aiming to reduce dependency on and extraction of plant-based raw materials while increasing the use of RF and meeting paper quality specifications.

Materials and Methods

Origin of raw materials

The sample of plant-based MCC was purchased directly from the supplier Synth. The samples of SF, LF, and RF were obtained from a paper industry in the South of Brazil that uses the Kraft production system. The samples were collected at the exit of the storage towers before being sent to the paper machines. The systems for obtaining pulp from cellulose (SF and LF) and RF are independent, meaning that at no point in the process do the fibers mix.

Characterization, formulation, and paper formation

On a bench scale, in the industry's laboratory simulating the paper machine steps, the experiment was conducted as exemplified in Figure 1.

The samples of SF, LF, and RF were characterized according to the internal control parameters of this industry, and the parameters listed in Table 1 were analyzed.

The samples of SF and LF were refined in a Hollander-type refiner until reaching a Freeness of approximately 450 mL, a value commonly practiced in the industry under study for papers with a basis weight of 120 $g.m^{-2}$. The mixtures were prepared in the agitator and the freeness and consistency were checked. A total of 6 formulations identified in Table 2 were tested, divided into two phases, the first test without the presence of MCC and the second test with MCC.

As per the agreement with the company, the data for SF, LF, and RF are not disclosed and are identified as X, Y, and Z, respectively. Only the data for MCC are described in percentages.

The assumptions for the formulations were as follows:

- The amount of SF was kept constant in all formulations, which is why it is identified as X.
- For formulation F0, the percentage proportions of SF and LF are practiced in the paper machines where this study was developed.
- For formulation F1, the percentage of LF (Y) in F0 was divided into 50% for LF (Y1) and 50% for RF (Z).
- For formulation F2, the percentage of LF was entirely removed and replaced with RF. Therefore, Y in F0 is equal to Z1 in F2, in terms of percentage.
- For formulations F3, F4, and F5, the percentage of RF in the recipe was reduced, and MCC was included.

The MCC was diluted in 250 mL of hot water and homogenized with constant stirring for 30 min. After preparation, the MCC was incorporated into the agitator along with the other fibers and mixed for 10 min.

Table 1 – Parameters analyzed and respective equipment and methodologies used.

Variables	Methodology
pH	Potentiometric—Mettler Toledo FP30 equipment
Conductivity	
Consistency	Gravimetry
Freeness	Canadian Standard Method (CSF), TAPPI T227 standard

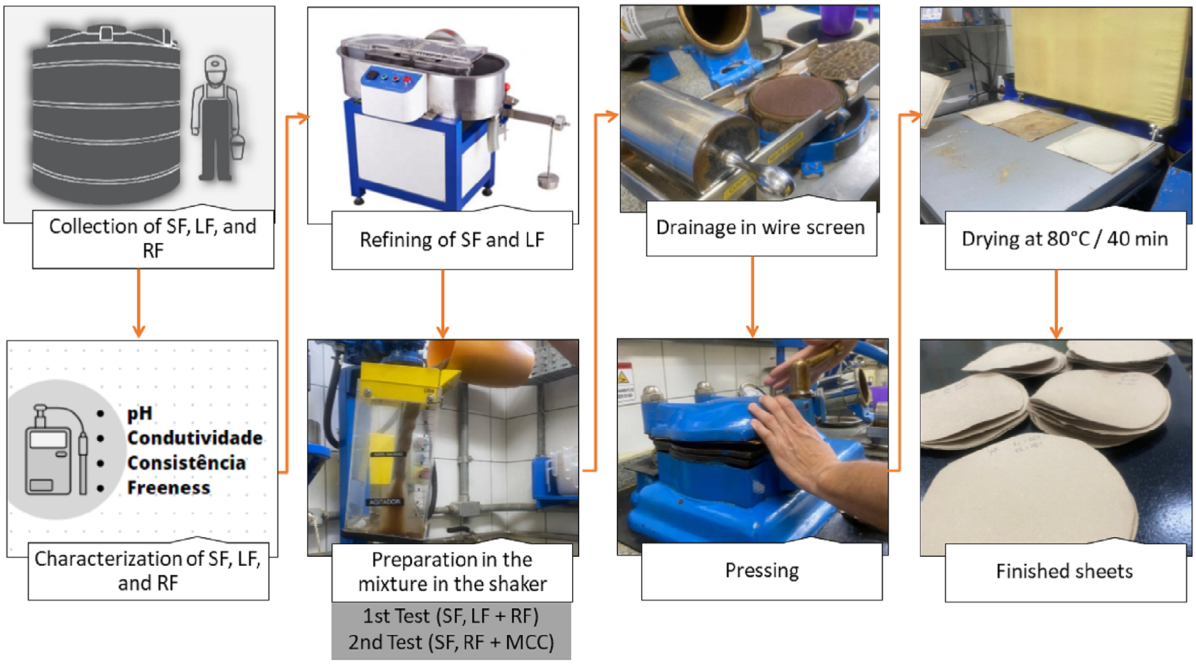

Figure 1 – Process stages for sheet formation.

The mixture of each formulation that was prepared in the agitator was drained through a sieve plate, resulting in the formation of the sheet.

The drained amount was determined based on the consistency of each formulation to create a sheet with a basis weight of 120 $g \cdot m^{-2}$ using a simple proportional rule (Equation 1). For the calculation, the following factors were considered:

- Area of the sheet-forming equipment=200 cm^2=0.02 m^2

$$\text{Grammage } (g \cdot m^{-2}) = \text{dry mass } (g) \div \text{area } (m^2) \quad (1)$$
$$120\ (g \cdot m^{-2}) = \text{dry mass} \div 0.02\ (m^2)$$
$$\text{dry mass} = 2.4\ g$$

- A sample with 2.4 g of dry mass was obtained from laboratory analysis with a volume of 600 mL and a consistency of 0.4%.
- Once the formulation was ready, the consistency of the sample was verified, and the necessary volume to drain in the sheet-forming equipment was calculated using a simple proportional rule (Equation 2).

$$\text{Drained volume } (\text{mL}) = \text{formulation consistency } (\%) \times 600/0.4 \quad (2)$$

The formed sheets were pressed at 4.0 $kgf \cdot cm^{-2}$ and dried at approximately 80°C for 40 min.

In total, six formulations were tested, and for each of them, eight sheets of paper with an average basis weight of 120 $g \cdot m^{-2}$ were obtained. No repetitions were performed.

Analysis of the physical properties of the sheet

The physical properties of the sheets (Table 3) were analyzed in the laboratory of the industry under study.

Table 2 – Identification of each paper formulation with *Eucalyptus spp.*, *Pinus spp.*, recycled fiber, and microcrystalline cellulose.

	Formulations	SF	LF	RF	MCC (%)
First Test	F0	X	Y	0	0
	F1	X	Y1	Z	0
	F2	X	0	Z1	0
Second Test	F3	X	0	Z2	6
	F4	X	0	Z3	12
	F5	X	0	Z4	24

SF: *Eucalyptus spp.*; LF: *Pinus spp.*; RF: recycled fiber; MCC: microcrystalline cellulose.

Table 3 – Physical tests conducted on the formed sheets.

Tests	Units
Grammage	$g \cdot m^{-2}$
Humidity	%
Porosity Gurley	$S.100\ mL^{-1}$
Traction Z	Psi
SCT (STFI)	$KN \cdot m^{-1}$
Mullen	Psi

The tests were conducted using the same methodology and equipment as the analyses performed on paper for sale under standard conditions of 50±2% relative humidity and 23±1°C temperature.

To mitigate the influence of basis weight variation among the samples, the tensile, compression, and burst indices were calculated, which are the ratios between the values obtained from the tests and the basis weight of the same sample (Equations 3, 4 and 5).

$$\text{Tensile index (TI)} = \text{Tensile Z} \div \text{grammage} \quad (3)$$

$$\text{Compression index (CI)} = \text{SCT} \div \text{grammage} \quad (4)$$

$$\text{Bursting index (BI)} = \text{Mullen} \div \text{grammage} \quad (5)$$

Results and Discussions

Fiber characterization and refinement

The data for the characterization of MCC, a fine, lightweight, white, odorless powder, are described in Table 4.

The commercial MCC used in this study meets all requirements. It is produced from highly purified pulp, with an average particle size by laser diffraction of 21–153 µm and a density of 0.30 $g \cdot mL^{-1}$. It is partially depolymerized, with a degree of polymerization below 350 n.

The requirements (limits) are internal parameters of the supplier (Labsynth Produtos para Laboratório Ltda). The methodology used for the analytical reagent is based on the guidelines of the American Chemical Society (ACS). If the requirements are not met, the product is not sold.

The data for the fiber characterization are described in Table 5.

Table 4 – Physical-chemical characterization of microcrystalline cellulose.

Parameters	Limits	Results
pH	5.0–7.0	6.67
Density	0.26–0.34 $g \cdot mL^{-1}$	0.30 $g \cdot mL^{-1}$
Particle distribution – D10	<30	21
Particle distribution – D50	40–75	65
Particle distribution – D90	>80	153
Degree of polymerization	Max. 350 n	219 n
Heavy metals	Max. 0.001%	<0.001%
Loss on drying	Max. 7.0%	3.68%
Water-soluble substance	Max. 0.24%	<0.24%

Source: Labsynth.

Table 5 – Physical-chemical characterization of *Eucalyptus spp.*, *Pinus spp.*, and recycled fiber.

Parameters	SF	LF	RF
pH	10,47	10,83	6,69
Conductivity ($\mu S \cdot cm^{-1}$)	2.858	770	1.410
CSF (mL)	723	772	562
Consistency (%)	10,51	9,71	3,34

SF: *Eucalyptus spp.*; LF: *Pinus spp.*; RF: recycled fiber.

The pH is one of the most important control variables in paper manufacturing. At high pH levels, above 8, as in this study, there is an increase in anion ionization, a decrease in fiber stiffness, and an increase in resistance capacity (refining and hydrogen bonding) (Lima, 2012). The pH of the RF is close to neutrality.

Conductivity measures the total dissolved ions (organic and inorganic) in the pulp, especially sodium, calcium, and magnesium, ranging from less than 10 mS (clean circuit) to 1000 mS (highly charged circuit). High conductivity affects the action of chemical additives, especially polymers, causing a loss of efficiency in mineral charge retention. Additionally, it reduces the tensile strength because it occupies the spaces where fiber-to-fiber contact used to occur, increasing the sensitivity to sheet breakage (Ahola, 2006; Lima, 2012). The industry under study has a clean circuit (below 10 mS), even with the use of RF.

Freeness indicates the degree of refining, a crucial step for paper quality. Refining promotes extensive fiber-to-fiber contact, resulting in increased burst and tensile strength. However, the process also cuts and reduces the size of fibers, leading to a reduction in tear strength and the formation of fines, which can harm paper formation and drainage on the flat table. Therefore, it is necessary to find a balance in refining intensity and time (D'Almeida, 1988; Smook, 1989).

The data from the refining process are described in Table 6.

Evaluating the refining process, it is possible to observe that LF is indeed more resistant than SF because both were in the same initial Freeness range, and it took more time to reach a Freeness of approximately 450 mL for LF, which is a value commonly practiced in the industry for papers with a basis weight of 120 g·m^{-2}.

Consistency quantifies the percentage of absolutely dry cellulose present in the sample. The samples collected at the storage tower exit had consistencies of 10.51 and 9.71% for SF and LF, respectively. Consistencies within the storage towers tend to be higher to occupy more space with cellulose instead of water. After refining, the consistencies were 1.21 and 1.32% for SF and LF, respectively. It is necessary to reduce the consistency for a more uniform deposition of the mixture on the paper-forming wire.

Table 6 – Refining of virgin fiber between 400 and 450 mL.

Parameters	SF	LF
CSF (mL) Initial	772	723
Refining time (min)	20	51
CSF (mL) final	444	456
Consistency (%)	1.21	1.32

SF: *Eucalyptus spp.*; LF: *Pinus spp.*

In practice, on a machine, the paper sheet is formed through a section composed of the headbox and flat table. The headbox's function is to evenly distribute fibers from an aqueous suspension with a consistency between 0.3 and 1.5% along the forming wire with a constant volumetric flow and uniform concentration. The flat table, which supports the sheet-forming wire, aims to remove as much water as possible from the fibers through drainage (Drummond, 2004; Lima, 2012).

Quality assessment

Table 7 displays the quality specifications for 120 g·m^{-2} paper from the company in which this study was conducted. Paper is considered out of specification only if it does not meet the maximum or minimum specification values, when applicable. "Target" refers to the company's objective values in this study.

All the formulations passed the humidity test (water content in the paper). The grammage is the weight that corresponds to the density of the paper (D'Almeida, 1988). To produce a paper with a defined grammage on a bench scale, the amount (grams) of each item (SF, LF, RF, and MCC) in the formulation is calculated. As with every experiment, there are oscillations and deviations, which is why the F5 sample did not pass the grammage test, as it exceeded the limit of 125 g·m^{-2}.

None of the formulations passed the porosity test, which is related to the paper's resistance to air penetration (D'Almeida, 1988). It can be observed that after the addition of MCC, the values decreased even further because there is greater interaction between the fibers and bonds, reducing the voids on the paper surface (Vaezi et al., 2019; Akter et al., 2020; Jin et al., 2021). This is favorable for reducing the absorption of oils, especially in packaging used for food. However, the industry under study requires the porosity to be at least 20 S.100 mL^{-1} to absorb graphic inks during the printing of the design requested by the customer. Therefore, new studies evaluating this parameter are necessary, such as refining adjustments to achieve a lower Freeness.

Table 7 – Physical tests and their respective specifications for the 120 g·m^{-2} paper.

Tests	Units	Limits			Formulations					
		Min.	Target	Max.	F0	F1	F2	F3	F4	F5
Grammage	g·m^{-2}	115	120	125	124.8	124.6	124.9	124.8	123.3	126*
Humidity	%	5.5	7.5	9.5	8.6	8.1	8.8	7.5	7.4	6.8
Porosity Gurley	S.100 mL^{-1}	20	50	–	9.9*	4.3*	6.2*	4.1*	3.6*	3.5*
Traction Z	Psi	35	42	–	49.5	48.2	43.0	48.4	42.3	41.1
SCT (STFI)	KN·m^{-1}	2.9	3.1	–	3.17	3.10	2.94	3.10	2.94	2.79*
Mullen	Psi	–	70	–	85.5	84.2	68.7	72.7	60.6	59.2

*Not approved.

In the study by Esteves et al. (2023), the fibers evaluated after refining showed an increase in porosity and interstitial spaces within the fiber wall. The longer the refining time, the greater the collapse of fibers, leading to increased fines generation and filling of paper pores, both of which make air passage more difficult (Mutjé et al., 2005; Bortolan, 2012). Additionally, after the refining process, there is a breakage of hydrogen bonds between cellulose and hemicellulose molecules, facilitating water penetration and fiber swelling, a phenomenon known as internal fibrillation, which consequently increases porosity (Clark, 1985).

Z-Traction and Traction Index

All papers passed the Z-direction tensile test. This test is performed by applying tension perpendicular to the sheet's plane and quantifies the resistance of internal bonds within the sheet's limits (D'Almeida, 1988).

In the first test (MCC=0%), as seen in Figure 2, it can be observed that the higher the percentage of RF, the lower the tensile strength of the paper. There was a 13.2% reduction in the tensile index in F2 compared with F0. This result is related to the fact that intrinsic strength and fiber size are directly proportional (Ebeling, 2000), meaning that with the substitution of *Pinus spp.* (LF) with RF (SF), the final pulp had a higher concentration of smaller fibers, resulting in greater filling of the space between the fibers and less interlocking between them.

In the second test (MCC>0%) for F3, the Z-direction tensile values increased by 9.5% compared with F2. This result can be mainly attributed to the fact that microscale cellulose contains many hydroxyl and carboxyl groups that can react with the hydroxyl groups of the cellulose pulp, causing an increase in bonding strength (Jin et al., 2021).

For F4 and F5, with 12 and 24% MCC, respectively, there was a decrease in the tensile index. The study by Vaezi et al. (2019) evaluated the addition of a nanocomposite (cationic starch + nanocrystalline cellulose) in the coating of Kraft paper sheets. In their observations using a transmission electron microscope, the authors found that for the nanocomposite with 3 and 5% nanocrystalline cellulose, the distribution of nanoparticles was uniform, while for the nanocomposite with 7% nanocrystalline cellulose, some areas had attached nanoparticles, forming small clusters and causing a decrease in the tensile index. Huang et al. (2018) also noted that one of the disadvantages of MCC is its large particle size, which can restrict its homogeneous distribution in composites.

Compressive Strength Test and Compression Index

The paper formed with formulation 5 (F5) was not approved due to low strength in the SCT test. This test evaluates the compressive force applied laterally to the specimen, as defined by STFI – Packforsk (D'Almeida, 1988).

As observed in the first test (MCC=0%), Figure 3 shows that the higher the percentage of RF, the lower the paper's compression resistance, as each cycle of RF processing results in a decrease in mechanical properties associated with strength (Hubbe et al., 2007). There was a 7.3% reduction in the compression index in F2 compared with F0.

In the second test (MCC>0%), after adding 6 and 12% MCC to F3 and F4, respectively, there was an increase in the compression index of 2.6 and 1.3%, respectively, compared with F2. With good distribution and dispersion, the use of MCC can compensate for the decrease in strength associated with the use of RF. This is related to the physical characteristics of MCC, such as high surface area and biocompatibility, which promote increased interfacial adhesion and the formation of a strong and compression-resistant interconnection structure (Mondal, 2018).

In the study by Starkey et al. (2021), *Pinus spp.* fibers with a high lignin content were used to produce micro and nanoscale cellulose with low levels of fibrillation, referred to as LMNFC. This mixture was added to the RF pulp from an industry in proportions of 1, 2, and 3%. The incorporation of LMNFC increased tensile strength by 20% while also improving STFI.

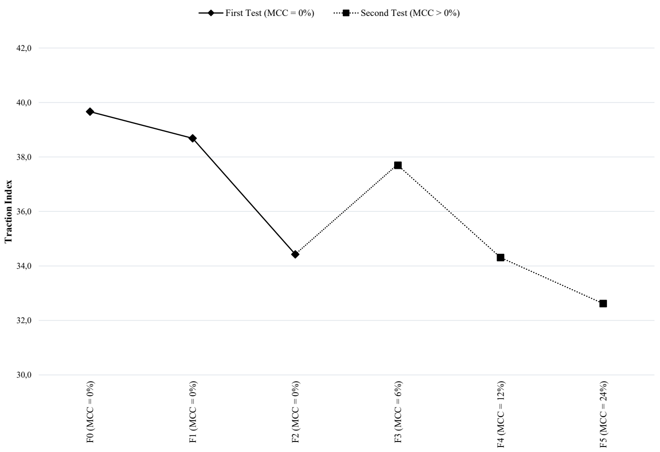

Figure 2 – Tensile index.

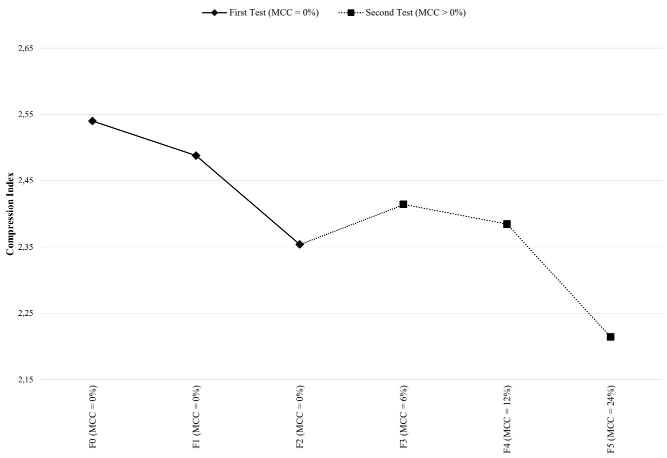

Figure 3 – Compression index.

For F5, with 24% MCC, a decrease in the compression index is observed. Lu and Drzal (2010) reported that there is a limit to the concentration of nanocomposites, above which fibers would start to aggregate, causing a reduction in the strength and elasticity of the material.

Mullen and Burst Index

All papers passed the Mullen test. This is a test of bursting strength, which refers to the pressure required to produce material rupture transmitted by an elastic diaphragm of circular area through the "Mullen"-type apparatus; the result depends on the degree of refinement, basis weight, and thickness (D'Almeida, 1988).

In the first test (MCC=0%), it is observed in Figure 4 that the higher the percentage of RF, the lower the paper's resistance. There was a 19.5% reduction in the burst index in F2 compared with F0. During pulping, approximately 90% of lignin is removed, and when these fibers go through the recycling process, repeated drying and rewetting operations, they become fibrillated and hardened, reducing their bonding potential and flexibility. The interfiber bonding (interaction of functional binding groups such as carboxyl, hydroxyl, and carbonyl) is strongly affected (Fernandes et al., 2010; Hubbe et al., 2007). Biotechnology is providing solutions to address this issue. Studies demonstrate that the addition of enzymes to the process can improve the quality of the fibers by assisting in the biopolishing of their walls and surfaces, as well as in the recovery of rehydration capacity, favoring the flexibility of the biopolished fibers (Bajpai, 2011).

In the second test (MCC>0%), there is a slight increase (2.7%) in the Burst Index for F3 compared to F2. However, for F4 and F5, there is a trend of a sharp reduction because smaller fibers are less flexible. Thus, MCC contributes to increasing the stiffness of the paper and reducing its flexibility due to its microstructure (Menegazzo, 2012).

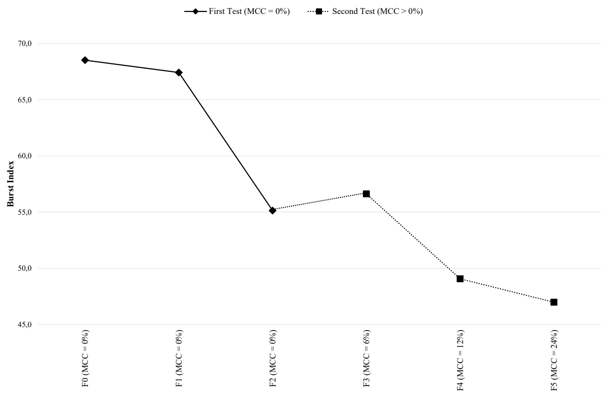

Figure 4 – Burst index.

Pulps with a longer average fiber length produce paper with better burst indices because the number of covalent bonds that connect the polysaccharide monomers, the longer the bond, the greater the resistance to rupture (Castanho, 2002).

Conclusions

In this study, new paper formulations were developed and tested using virgin fibers (SF and LF), RF, and MCC. Formulation 3 (F3) with 6% MCC was the best option to achieve a paper with complete elimination of LF while meeting the strength standards (Z-traction, SCT, and Mullen). For formulation 5 (F5) with 24% MCC, there was a decrease in strength, indicating that there is a limit to the addition of MCC. Beyond this limit, the fibers begin to aggregate, making distribution less uniform and promoting a reduction in tensile strength, compression, and burst strength. None of the formulations passed the porosity test, suggesting that further studies will be necessary. This study proposes a new path for sustainable packaging solutions, demonstrating that the addition of up to 6% MCC can strengthen RFs and reduce dependence on and extraction of *Pinus spp.*, which is primarily responsible for providing strength in packaging.

Contribution of authors

VAN TIENEN, Y.M.S.: conceptualization, data curation, formal analysis, investigation, and methodology. RODRIGUES, S.A.: supervision, review & editing.

References

Ahola, T., 2006. Intelligent estimation of web break sensitivity in paper machines. Doctoral Thesis, University of Oulu, Finland. Retrieved 2023-23-07, from https//jultika.oulu.fi/Record/isbn951-42-7957-3

Akter, T.; Nayeem, J.; Quadery, A. H.; Razzaq, M.A.; Uddin, M.T.; Bashar, M.S.; Jahan, M.S., 2020. Microcrystalline cellulose reinforced chitosan coating on Kraft paper. Cellulose Chemistry and Technology, v. 54, (1-2), 95-102.

Associação Brasileira de Embalagem (ABRE), 2022. Dados do Setor (Accessed June 29, 2023) at:. https://www.abre.org.br/dados-do-setor/.

Bajpai, P., 2011. Biotechnology for pulp and paper processing. Springer, New York.

Bortolan, R.H., 2012. Estudo do efeito do tipo de celulose utilizada e da intensidade de refino no processo de refino da polpa celulósica. Monografia, Pós-Graduação Lato Sensu em Tecnologia de Celulose e Papel, Universidade Presbiteriana Mackenzie, São Paulo. Retrieved 2023-03-03, from https//dspace.mackenzie.br/handle/10899/243

Castanho, C.G., 2002. Utilização de rejeito fibroso industrial da polpação Kraft de eucalipto para produção de papéis. Dissertação de Mestrado em Ciência Florestal, Universidade Federal de Viçosa, Viçosa. Retrieved 2023-10-06, from http://locus.ufv.br/handle/123456789/3189

Ceron, A., 2021. Santa Catarina terá programa voltado ao desenvolvimento florestal (Accessed July 25, 2023) at:. https://www.agricultura.sc.gov.br/santa-catarina-tera-programa-voltado-ao-desenvolvimento-florestal/.

Clark, J.d'A., 1985. Pulp technology and treatment for paper. Miller Freeman Publications, Inc., San Francisco.

D'Almeida, M.L.O., 1988. Celulose e papel: tecnologia de fabricação de pasta celulósica. 2. ed. v. 2. IPT-SENAI, São Paulo, 559 p.

Didone, M.; Saxena, P.; Brilhuis-Meijer, E.; Tosello, G.; Bissacco, G.; Mcaloone, T.C.; Pigosso, D.C.A.; Howard, T.J., 2017. Moulded pulp manufacturing: overview and prospects for the process technology. Packaging Technology and Science, v. 30, (6), 231-249. https://doi-org.ez48.periodicos.capes.gov.br/10.1002/pts.2289

Didone, M.; Tosello, G., 2019. Moulded pulp products manufacturing with thermoforming. Packaging Technology and Science, v. 32, (1), 7-22. https://doi-org.ez48.periodicos.capes.gov.br/10.1002/pts.2543

Drummond, D.M.D., 2004. Otimização para o posicionamento dos equipamentos do circuito de massa na fabricação de papel Tissue. Dissertação de Mestrado, Faculdade de Engenharia Química, Desenvolvimento de Processos Químicos, Universidade Estadual de Campinas, São Paulo. doi:10.47749/T/UNICAMP.2004.307744. Retrieved 2023-11-05, from www.repositorio.unicamp.br

Ebeling, K., 2000. Role of softwood fibre form and condition on its reinforcement capability. Cellulosic Pulps, Fibres and Materials, Woodhead Publishing, 209-225. https://doi.org/10.1533/9781845698546.209

Esteves, C.V.; Brännvall, E.; Stevanic, J.S.; Larsson, P.T., 2023. Pulp delignification and refining: impact on the supramolecular structure of softwood fibers. Celulose, v. 30, 10453-10468. https://doi.org/10.1007/s10570-023-05490-4

Fernandes, S.C.M.; Freire, C.S.R.; Silvestre, A.J.D.; Desbrières, J.; Gandini, A.; Neto, C.P., 2010. Production of coated papers with improved properties by using a water-soluble chitosan derivative. Industrial and Engineering Chemistry Research, v. 49, (14), 6432-6438. https://doi.org/10.1021/ie100573z

Food and Agriculture Organization of the United Nations (FAO), 2021. Forestry Production and Trade (Accessed March 11, 2023) at:. https//www.fao.org/faostat/en/#data/FO

Forest Stewardship Council (FSC), 2015. Principios y Criterios del FSC para el Manejo Forestal Responsible (FSC-STD-01-001 V5-2 ES) (Accessed March 11, 2023) at:. https://br.fsc.org/br-pt/fsc/principios-criterios.

Fouad, H.; Kian, L.K.; Jawaid, M.; Alotaibi, M.D.; Alothman, O.Y.; Hashem, M., 2020. Characterization of Microcrystalline Cellulose Isolated from Conocarpus Fiber. Polymers, v. 12, (12), 2926-2937. https://doi.org/10.3390/polym12122926

Galati, A.; Gianguzzi, G.; Tinervia, S.; Crescimanno, M.; La Mela Veca, D.S., 2017. Motivations, adoption and impact of voluntary environmental certification in the Italian Forest based industry: The case of the FSC standard. Forest Policy and Economics, v. 83, 169-176. https://doi.org/10.1016/j.forpol.2017.08.002

German, J.D.; Redi, A.A.N.P.; Prasetyo, Y.T.; Persada, S.F.; Ong, A.K.S.; Young, M.N.; Nadlifatin, R., 2022. Choosing a package carrier during COVID-19 pandemic: An integration of pro-environmental planned behavior (PEPB) theory and service quality (SERVQUAL). Journal of Cleaner Production, v. 346, 131123. https://doi.org/10.1016/j.jclepro.2022.131123

Horejs, C., 2020. Solutions to plastic pollution. Nature Reviews Materials, v. 5, 641. https://doi.org/10.1038/s41578-020-00237-0

Huang, X.; Xie, F.; Xiong, X., 2018. Surface-modified microcrystalline cellulose for reinforcement of chitosan film. Carbohydrate Polymers, v. 201, 367-373. https://doi.org/10.1016/j.carbpol.2018.08.085

Hubbe, M.A.; Venditti, R.A.; Rojas, O.J., 2007. What happens to cellulosic fibers during papermaking and recycling? A review. BioResources, v. 2, (4), 739-788.

Indústria Brasileira de Árvores (IBÁ), 2022. Dados Estatísticos. São Paulo (Accessed March 10, 2023) at: https://www.iba.org/dados-estatisticos.

Jin, K.; Tang, Y.; Liu, J.; Wang, J.; Ye, C., 2021 Nanofibrillated cellulose as coating agent for food packaging paper. International Journal of Biological Macromolecules, v. 168, 331-338. https://doi.org/10.1016/j.ijbiomac.2020.12.066

Jochem, D.; Bösch, M.; Weimar, H.; Dieter, M., 2021. National wood fiber balances for the pulp and paper sector: An approach to supplement international forest products statistics. Forest Policy and Economics, v. 131, 102540. https://doi.org/10.1016/j.forpol.2021.102540.

Klemm, D.; Kramer, F.; Moritz, S.; Lindström, T.; Ankerfors, M.; Grey, D.; Dorris, A., 2011. Nanocelluloses: a new family of nature-based materials. Angewandte Chemie International Edition, v. 50, ed. 24, 5438-5466. https://doi.org/10.1002/anie.201001273

Lauri, P.; Forsell, N.; Fulvio, F.D.; Snäll, T.; Havlik, P., 2021 Material substitution between coniferous, non-coniferous and recycled biomass – Impacts on forest industry raw material use and regional competitiveness. Forest Policy and Economics, v. 132, 1025882021. https://doi.org/10.1016/j.forpol.2021.102588

Lima, A.S., 2012. A química da parte úmida em produção de papel: conceitos e aplicações. Monografia, Pós-graduação em Tecnologia de Celulose e Papel, Universidade Presbiteriana Mackenzie, São Paulo. Retrieved 2023-23-07, from https//dspace.mackenzie.br/handle/10899/146

Lu, J.; Drzal, L.T., 2010. Microfibrillated cellulose/cellulose acetate composites: effect of surface treatment. Journal of Polymer Science Parte B: Polymer Physics, v. 48, (2), 153-161. https://doi.org/10.1002/polb.21875

Macleod, M.; Arp, H.P.H.; Jahnke, A., 2021. The global threat from plastic pollution. Science, v. 373, (6550), 61-65. https://doi.org/10.1126/science.abg5433

Menegazzo, M.L., 2012. Características morfológicas de celuloses branqueadas de Pinus e Eucalyptus em analisador óptico automático de fibras. Dissertação de Mestrado, Faculdade de Ciências Agronômicas, Universidade Estadual Paulista, Botucatu. Retrieved 2023-18-06, from http://repositorio.unesp.br/handle/11449/99750

Merci, A.; Urbano, A.; Grossmann, M.V.E.; Tischer, C.A.; Mali, S., 2015. Properties of microcrystalline cellulose extracted from soybean hulls by reactive extrusion. Food Research International, v. 73, 38-43. https://doi.org/10.1016/j.foodres.2015.03.020

Mondal, S., 2018. Review on nanocellulose polymer nanocomposites. Polymer-Plastics Technology and Engineering, v. 57, (13), 1377-1391. https://doi.org/10.1080/03602559.2017.1381253

Mutjé, P.; Pèlach, M.A.; Vilaseca, F.; García, J.C.; Jiménez, L., 2005. A comparative study of the effect of refining on organosolv pulp from olive trimmings and kraft pulp from eucalyptus wood. Bioresource Technology, v. 96, (10), 1125-1129. https://doi.org/10.1016/j.biortech.2004.10.001

Nechita, P.; Roman, M., 2020 Review on polysaccharides used in coatings for food packaging papers. Coatings, v. 10, (6), 566. https://doi.org/10.3390/coatings10060566

Sharma, M.; Agudo, R.; Murtinho, D.; Valente, A.J.M.; Sousa, A.P.M.; Ferreira, P.J.T., 2020. A review on cationic starch and nanocellulose as paper coating componentes. International Journal of Biological Macromolecules, v. 162, 578-598. https://doi.org/10.1016/j.ijbiomac.2020.06.131

Smook, G.A., 1989. Handbook for pulp and paper technologists. TAPPI, Atlanta, 419 p.

Starkey, H.; Chenoweth, A.; Johnson, C.; Salem, K.S.; Jameel, H.; Pal, L., 2021. Lignin-containing micro/nanofibrillated cellulose to strengthen recycled fibers for lightweight sustainable packaging solutions. Carbohydrate Polymer Technologies and Applications, v. 2, 100135. https://doi.org/10.1016/j.carpta.2021.100135

Unnikrishnan, A.; Figliozzi, M., 2021. Exploratory analysis of factors affecting levels of home deliveries before, during, and post - COVID-19. Transportation Research Interdisciplinary Perspectives, v. 10, 100402. https://doi.org/10.1016/j.trip.2021.100402

Vaezi, K.; Asadpour, G.; Sharifi, S.H., 2019. Effect of coating with novel bio nanocomposites of cationic starch/cellulose nanocrystals on the fundamental properties of the packaging paper. Polymer Testing, v. 80, 106080. https://doi.org/10.1016/j.polymertesting.2019.106080

World Economic Forum, 2022. Top 25 recycling facts and statistics for 2022 (Accessed November 01, 2022) at:. https://www.weforum.org/agenda/2022/06/recycling-global-statistics-facts-plastic-paper/.

Zhang, Y.; Duan, C.; Bokka, S.K,; Ele, Z.; Ni, Y., 2022. Molded fiber and pulp products as green and sustainable alternatives to plastics: A mini review. Journal of Bioresources and Bioproducts, v 7, (1), 14-25. https://doi.org/10.1016/j.jobab.2021.10.003