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Analysis of Cellulose Pulp Characteristics and Processing Parameters for Efficient Paper Production

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Abstract: For economic reasons, increasing the use of various fibrous pulps with high lignin contents—i.e., chemothermomechanical pulp (BCTMP and CTMP), thermomechanical pulp (TMP), and semichemical pulp—is desirable. The relatively good quality and increased efficiency of these pulps make them attractive paper semi-products. In particular, they could alleviate the severe shortage of paper semi-products. Although mechanical pulp and semichemical pulp are achieving increasing quality with substantially increased wood efficiency, their production is often characterised by high consumption of electricity to defibre chips or refine high-lignin-content fibrous pulps. Technological, environmental, and economic evaluations of the manufacture and application of increased efficiency cellulose pulps that take into account potential profits from increased cellulose pulp efficiency and losses due to energy costs and degradation in the properties of the resulting paper are relevant and essential to paper mills. This article reports such an analysis. The authors have analysed the usable properties of ten cellulose pulps with various degrees of digestion and identified the optimum pulp that yields the optimum product properties, considering the yield; pulp refining time, which determines the cost of paper manufacture; and strength properties of the obtained paper.

Keywords: pulp yield; delignification degree; kappa number; high-efficiency cellulose pulp; papermaking

1. Introduction

Cellulose pulp is manufactured from raw plant materials, chiefly wood. It is the main ingredient and structural substance of paper and thus determines many of the properties of paper products [1–3].

At present, the annual global production of cellulose pulp is approximately 180 million tons [4], and demand for this product is continuously growing [5]. In addition to increasing demand for paper-related purposes, cellulose pulp is being more widely applied in a variety of economic and technical areas, such as medicine, gastronomy, and household goods, due to its functionality, recyclability, and, most importantly, its biodegradability [6–8].

At present, in Europe, 43 million tons of cellulose pulp is consumed per year [5]. A European Union directive (COM/2018/340 final—2018/0172 (COD)) prohibiting the sale of disposable products made of standard plastics takes effect in 2021 and will undoubtedly provide a major stimulus for further growth in the consumption of cellulose pulp in Europe. These products will have to be replaced with alternative biodegradable products, among which paper-based products are expected to predominate. These products must meet the relevant standards of quality, sterility, aesthetics, and biodegradability for their intended uses [9–13]. Importantly, to comply with other European Union directives, scrap paper pulp, which is easily accessible and relatively inexpensive, will not be suitable for use in many of these products for health reasons [14–19].

Based on the above considerations, sustainable growth in the consumption of cellulose pulp is expected. However, there is a growing deficit of raw wood materials [20–22], with the paper industry already consuming over 10% of global wood production [23,24]. In addition to increasing the resource base of the paper industry—e.g., through more reasonable use of existing forest resources, the development of plantations of fast-growing trees, or the use of one-year fibrous raw materials [25–28]—enhancing the efficiency of the pulp manufacturing process is crucial for increasing the production of cellulose pulp [29,30]. Even slight improvements in the efficiency of this process may lead to high revenue.

Cellulose pulp is manufactured by the chemical digestion of fibrous plant materials, mainly wood. At present, the sulphate method of cellulose pulp production is prevalent. This method involves treating the raw wood material with a cooking liquor comprised of a mixture of NaOH and Na_2S [31]. It produces wood pulp with good usable properties [32,33], allows for the easy recovery of chemicals and heat coupled with the disposal of organic waste, and decreases the volume of contaminants in the discharged wastewater, which mitigates the harmful effects of pulp mills on the environment [34–37]. In sulphate digestion, the majority of the lignin, which binds the cellulose fibres, is dissolved and leached from the raw wood material. Unfortunately, this process is not fully selective and a substantial fraction of the hemicelluloses and cellulose that make up the cellulose fibres also undergo degradation [31]. In this respect, the efficiency of wood pulp manufacture for papermaking purposes is only 40–55% [38].

The efficiency of paper pulp production from wood depends on the manufacturing process and chemical composition of the used wood [39,40]. In turn, the wood digestion process is affected by fluctuations in the lignin content of the raw wood material [41–43]. Unfortunately, typical methods for the direct quantitative determination of lignin are very labour- and time-intensive. In comparison, the Kappa number is relatively easier to determine. The Kappa number is a measure of the degree of fibrous pulp digestion and can be applied to determine lignin content [44–46]. Its value can vary from 0 for practically lignin-free wood pulp (bleached wood pulp) to approximately 60 (standard unbleached wood pulp) [47]. Higher Kappa numbers correspond to high-efficiency and semichemical pulps.

Cellulose pulp produced under optimal conditions has a Kappa number of 45–46, which corresponds to an efficiency of 42–47% [48–50] in the production of paper pulp from wood. Various technologies can be applied to manufacture cellulose pulps with higher Kappa numbers and thus higher cellulose pulp efficiencies, such as the addition of agents to limit the depolymerisation of cellulose and hemicelluloses, e.g., anthraquinone and its derivatives, to the cooking liquor [51,52]. However, while methods to increase the efficiency of wood pulp above a Kappa number of 45–46 provide better efficiency, they have negative effects—principally, decreased quality of the obtained cellulose pulp. The most significant negative effects on the wood pulp quality are the following:

- Reduced brightness of the cellulose pulp [53];
- Reduced strength properties of the resulting paper [54,55];
- Poorer beatability, i.e., increased energy consumption in the refining of the cellulose pulp [56].

Diminished cellulose pulp brightness is of aesthetic significance in a variety of paper products; however, this parameter can be improved by bleaching the cellulose pulp with reagents such as hydrogen peroxide or sodium hyposulphite [57,58]. Many paper products do not require cellulose pulp with high strength properties; paper pulps with high Kappa numbers can be used for such products.

As a rule, an increased Kappa number of a cellulose pulp corresponds to poorer pulp beatability; that is, greater specific energy consumption is necessary to refine the wood pulp to a given refining degree (freeness approx. 30°SR) [59–61]. This is particularly important because the refining of fibrous paper pulp is an exceptionally energy-intensive process with a very poor energy efficiency ranging from several percent to several times this amount [62,63]. As a result, specific energy consumption in the fibrous pulp refining process is approximately 100–500 kWh/t [60,64], which represents roughly 40% of the overall electricity consumption of a paper mill. However, a substantial group of paper products can be manufactured from cellulose pulp with a low refining degree.

Based on the considerations presented above, the authors' purpose was to identify the delignification degree of pulp that yielded the optimum product properties, considering the yield, pulp refining time, and strength properties of the obtained paper. To achieve the objectives, the properties of ten paper pulps with varying delignification degrees were investigated in order to provide a basis for the technological and economic evaluation of the desirability of the manufacture and use of high-efficiency cellulose pulp.

2. Materials and Methods

2.1. Delignification Process

Pine wood (*Pinus sylvestris* L.) was used in this work. Cellulosic pine pulps were prepared using the sulphate method described by Modrzejewski et al. [65] from industrial woodchips containing 7–8% moisture. The materials were kept in a hermetically sealed container to avoid any changes to their humidity before treatment with NaOH and Na_2S solutions, which were prepared fresh before use. Active alkali at 20–38% was added (per batch), and the water-to-wood ratio (*v/w*) was 4. The dry weight (DW) of all the materials was determined before pulping.

The delignification processes were conducted in 15 dm^3 PD-114 stainless steel reactors (Danex, Katowice, Poland) with regulated temperature (using a water jacket) and agitation (three swings per minute, 60° swing angle). Suspensions of the disintegrated materials were heated for 120 min to achieve a temperature of 172 °C and incubated at this temperature for a further 120 min. The temperature was then decreased to 25 ± 5 °C using a jacket with cold tap water. After delignification, the material was washed several times with demineralised water and incubated overnight in demineralised water to remove the residual alkali-soluble fractions. The solids were disintegrated for 3 min in a laboratory JAC SHPD28D propeller pulp disintegrator (Danex, Katowice, Poland), and the fibres were screened using a PS-114 membrane screener (Danex, Katowice, Poland) equipped with a 0.2 mm gap screen. After screening, the pulps and shives were dried at room temperature (20 ± 2 °C) for 48 h and then weighted to determine the pulp and shive content. The dry pulps were stored in hermetically sealed vials until being used in further experiments.

The post-screening yields, shives content, and residual lignin contents expressed as the Kappa numbers (ISO 302:2015) of the pulps were determined. The average polymerisation degree of the cellulose contained in the pulps was determined using the viscometric method described in ISO 5351 (2010).

2.2. Chemical Analysis of Pulps

Analysis of the chemical composition of the cellulosic pulps included the quantification of extractives, lignin, cellulose, hemicelluloses, and ash. The lignin content was determined using a gravimetric method in compliance with the standard Tappi T222 (Acid-Insoluble Lignin in Wood and Pulp) after the removal of extractives according to the standard Tappi T204 (Solvent Extractives of Wood and Pulp). The content of holocellulose was determined according to the Tappi Useful Method 249 (Cellulose in Pulp). Alpha cellulose was quantified according to the standard Tappi T203 (Alpha, Beta and Gamma-Cellulose in Pulp). The content of hemicelluloses was calculated as the difference between the holocellulose and cellulose contents. Ash content was determined by a gravimetric method in compliance with standard Tappi T211 (Ash in Wood, Pulp, Paper and Paperboard—Combustion at 525 °C). All chemical analyses were performed in triplicate for each pulp.

2.3. Production of Paper Sheets

The pulps were used to prepare test sheets in the laboratory. Before processing, each pulp was soaked in water for 24 h. The cellulosic pulps were treated in a JAC SHPD28D laboratory propeller pulp disintegrator (Danex, Katowice, Poland) according to PN EN ISO 5263-1 (2006) at 23,000 revolutions. To determine the pulp and paper properties, the cellulosic pulps were refined to 30 ± 1°SR. The Schopper–Riegler freeness was measured using a Schopper–Riegler apparatus (Thwing-Albert Instrument Company, West Berlin, NJ, USA), according to PN-EN ISO 5267-1 (2002). The refining process was performed in a JAC PFID12X PFI mill (Danex, Katowice, Poland) according to PN-EN ISO 5264-2 (2011); a single batch consisted of 22.5 g of dry pulp. In the next step, sheets of paper were formed in a Rapid-Koethen apparatus in accordance with PN-EN ISO 5269-2 (2007). Each paper sheet had a basis weight of 80 g/m^2 (according to ISO 536:2012). Only sheets with basis weights between 79 and 81 g/m^2 were used for further investigation.

2.4. Analysis of Paper Properties

The test sheets were conditioned for 24 h at a temperature of 23 ± 1 °C and a relative humidity of 50 ± 2% (PN-EN ISO 187:1990) before the determination of their mechanical properties, namely, their tensile index, stretch, breaking energy (PN-EN ISO 1924-2:2010), burst index (PN-EN ISO 1974:2012), and tear index (PN-EN ISO 2758:2014-10). The brightness of the sheets was also measured (TAPPI T452).

3. Results and Discussion

Ten cellulose pulps from pine wood with delignification degrees ranging from approximately 20 to 90 in Kappa number were prepared for testing. This range of delignification degrees was obtained by varying the active alkali content from 20 to 38%. A comparison of the chemical make-ups of the obtained cellulose pulps is shown in Figure 1.

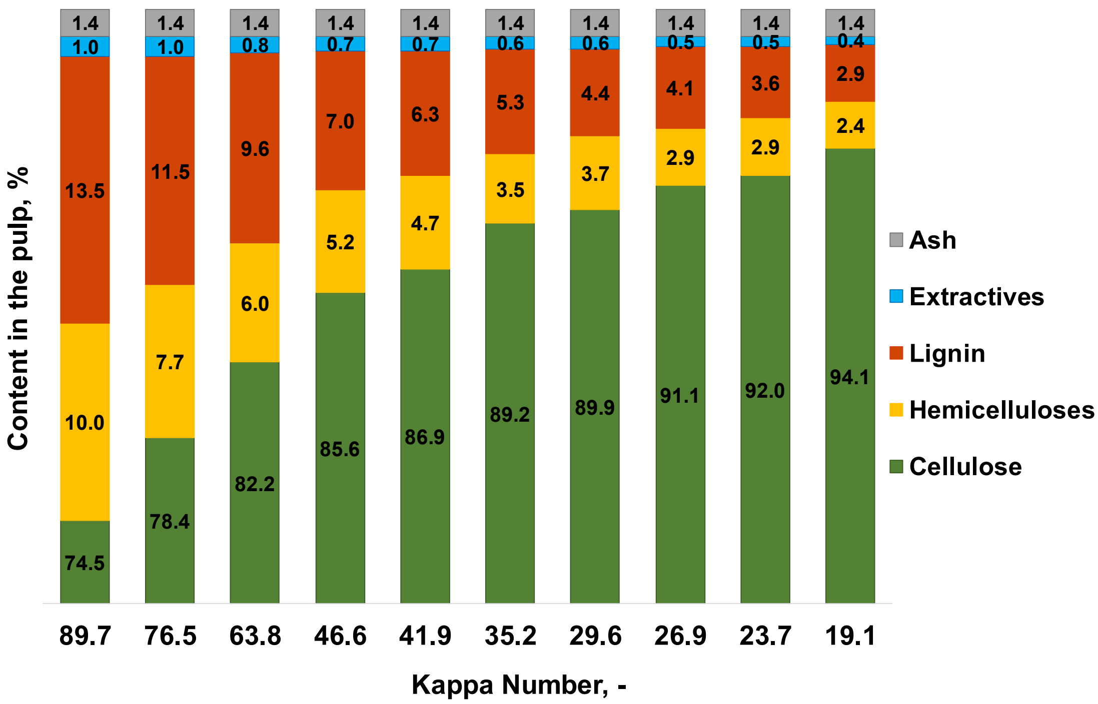

Figure 1. Chemical composition of the cellulosic pine pulps.

As shown in Figure 1, as the lignin content decreased from 13.5 to about 3% and the hemicellulose content decreased from 9.6 to 2.4% (with negligible change in the extractive content), the cellulose content of the manufactured wood pulp increased from 74.5 to 94.5%. The trace amount of extractives was attributed to their saponification and consequent dissolution in the alkaline sulphate solution as a result of the action of the alkali. The ash content in the pulps was constant, at approximately 1.4%, regardless of the cooking conditions.

As the Kappa number and lignin content decreased, depolymerisation and dissolution of the hemicelluloses and cellulose began to occur. These factors contributed to the decrease in the efficiency of the obtained wood pulp relative to that of the starting raw wood material (Table 1). The decrease in the Kappa number of the cellulose pulp from 90 to 20 led to a considerable decline in the efficiency of the wood pulp, from about 47 to about 37%.

Table 1. Properties of the pine cellulosic pulps with different delignification degrees.

Kappa Number	Pulp Yield	Shives	DP	Beatability
	[%]	[%]		[min]
89.7	47.2 (0.5)	3.10 (0.28)	1320 (35)	6.0
76.5	46.9 (0.4)	1.60 (0.26)	1312 (22)	5.8
63.8	45.7 (0.3)	1.00 (0.02)	1315 (4)	5.5
46.6	43.5 (0.4)	0.61 (0.03)	1227 (14)	5.1
41.9	42.3 (0.3)	0.46 (0.03)	1112 (10)	5.0
35.2	41.2 (0.1)	0.12 (0.01)	1024 (8)	4.8
29.6	40.5 (0.3)	0.08 (0.01)	929 (9)	4.5
26.9	39.4 (0.2)	0.05 (0.01)	856 (11)	4.3
23.7	38.5 (0.4)	0.01 (0.00)	752 (2)	4.0
19.1	36.9 (0.3)	0.00 (0.00)	599 (5)	3.2

Note: Standard deviations are given in brackets.

Notably, the so-called delignification selectivity indicator for the rate of dissolution of the sum of wood ingredients bears testimony to efficiency of cellulose pulp. At the initial stage of cooking, the delignification is poorly selective. The lignin selectivity improves as digestion proceeds but then deteriorates during the final stage of the process due to the high resistivity of a fraction of the lignin to digestion, while the polysaccharides dissolve extensively. Therefore, the removal of this resistant lignin fraction is difficult and unprofitable, since it results in reduced wood pulp efficiency and strength. For this reason, paper pulps with Kappa numbers lower than 25–30 are seldom manufactured industrially from softwood.

Importantly, the phenomena that decrease the efficiency of cellulose pulp also occur at high Kappa numbers. High-kappa-number, i.e., less-digested, cellulose pulps have greater lignin contents and numbers of shives (Table 1). The term shives refers to woodchips that have not been fully digested, in which the wood structure is partly preserved and the chip has not undergone defibration during the initial mechanic defibration process.

Under the conditions tested, as the Kappa number increased from 40 to 90, the content of shives in the cooking pulp increased from approximately 0.3 to 3%. As a result, with increasing Kappa number, the final productivity of the wood pulp production diminished gradually or the necessity to defibrate shives arose, which has a negative effect on printing quality and, in particular, on the whiteness of the manufactured cellulose pulp. Shives also reduce paper durability and are thus an undesirable component of paper pulp.

As the degree of wood pulp digestion increased (decreasing Kappa number), significant changes occurred in the cellulose pulp. A relatively large decline in the degree of cellulose polymerisation from 1270 to 600 was observed as the Kappa number decreased from 90 to 20 (Table 1).

The beatability of the wood pulp (refining time needed to achieve 30°SR), which is very important from economic and technological viewpoints, was also analysed (Table 1). This indicator characterises the ease of refining a fibrous wood pulp during its reprocessing into paper. Two parameters that can be used to evaluate beatability are the time required to refine the pulp to a specified degree (most frequently to 30°SR), called freeness, and the pulp freeness achieved using a given refining time under standardised conditions. Increases in this coefficient correspond to increased specific energy consumption in the refining of a given cellulose pulp.

As expected, as the lignin content in the wood pulp increased, the refining time necessary to achieve a given refining degree, and thus its beatability, also increased. As the Kappa number increased from 20 to 90, the beatability index of the paper pulp increased from approximately 3 to 6 min (Table 1). It can be therefore be concluded that this increase in the Kappa number resulted in an approximate doubling of the energy demand for refining. Thus, taking into account the very high specific energy consumption of the pulp refining process, the profitability of manufacturing hard-to-refine pulp must be considered, even though such pulp exhibits satisfactory papermaking properties (Table 2) and higher pulp productivity (Figure 2). The refining process, along with the price of the raw fibrous materials, has a decisive effect on the price of the end-product.

Table 2. Properties of paper sheets produced from pine pulps (freeness of 30 ± 1°SR).

Kappa Number	Brightness	Tensile Index	Breaking Energy	Stretch	Tear Index	Burst Index
	[%]	[N·m/g]	[J]	[%]	[mN·m^2/g]	[kPa·m^2/g]
89.7	16 (0)	8.33 (0.22)	0.207 (0.002)	3.09 (0.07)	5.25 (0.02)	6.75 (0.11)
76.5	17 (0)	8.85 (0.36)	0.215 (0.003)	3.02 (0.02)	5.75 (0.09)	6.81 (0.03)
63.8	18 (0)	9.40 (0.02)	0.245 (0.005)	3.25 (0.08)	6.00 (0.10)	7.00 (0.16)
46.6	20 (0)	9.56 (1.02)	0.255 (0.004)	3.32 (0.02)	6.13 (0.11)	7.38 (0.17)
41.9	21 (0)	9.09 (0.11)	0.236 (0.003)	3.24 (0.01)	5.88 (0.12)	6.75 (0.13)
35.2	23 (0)	8.12 (0.18)	0.219 (0.009)	3.36 (0.10)	5.75 (0.12)	6.63 (0.05)
29.6	25 (0)	7.51 (0.06)	0.199 (0.007)	3.31 (0.06)	5.81 (0.03)	6.50 (0.07)
26.9	27 (1)	7.28 (0.47)	0.187 (0.006)	3.21 (0.05)	5.75 (0.04)	6.50 (0.09)
23.7	28 (0)	6.77 (0.05)	0.157 (0.002)	2.90 (0.01)	5.75 (0.07)	6.38 (0.08)
19.1	31 (1)	6.36 (0.08)	0.162 (0.000)	3.17 (0.03)	5.63 (0.06)	6.25 (0.04)

Note: Standard deviations are given in brackets.

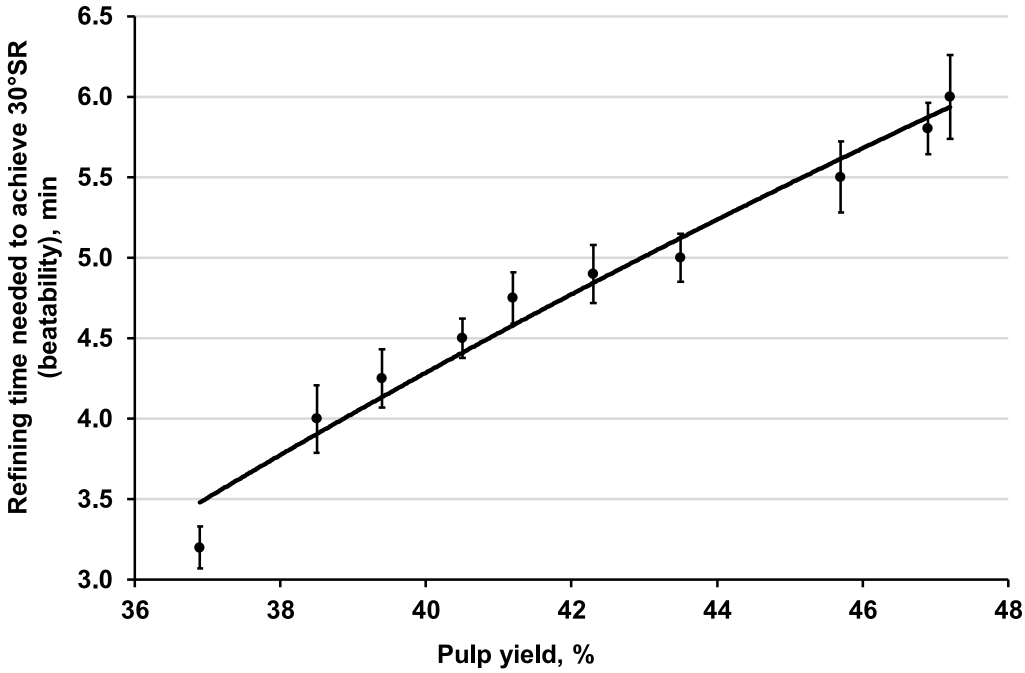

Figure 2. Relationship between the yield and beatability of the pulp.

Taking into account the higher energy consumption in the production of high-yield pulp, which leads to a higher price, the production of high-Kappa-number pulp is generally unbeneficial to the environment.

The optical properties of the resulting paper also deteriorate (Table 2) with increasing lignin content due to the reagents used in the digestion process, with the formation of chromophore groups characterised by much darker colours. The formation of coloured chromophore systems in lignin may occur as a result of its degradation through hydrolysis and oxidation reactions, among other causes. As the Kappa number increased from the optimal value of 47 (see discussion of strength indices below) to 90, the whiteness of the resulting paper decreased by 20%, and thus, high-yield pulp cannot be applied in the production of high-quality paper where high optical product properties are required.

Additionally, due to its dark colour, the bleaching procedures for high-yield pulp require a greater amounts of chemicals, which are often harmful to the environment. Notably, TCF bleaching (Totally Chlorine Free—bleaching without the use of chlorine compounds) requires a low initial Kappa number pulp to obtain full brightness and good strength properties due to the ability of the bleaching chemicals to degrade fibres. Additionally, TCF bleaching allows a high ISO brightness to be achieved without any loss of productivity. ECF bleaching (Elemental Chlorine Free—bleaching without the use of elemental chlorine) can be applied to high-Kappa-number pulp. For environmental and quality reasons, elemental chlorine and hypochlorite have been supplanted by other washing agents.

The significant changes in the wood pulp with the delignification degree had a significant impact on the tensile properties of the resulting paper (Table 2). The data in Table 2 show that the highest strength indices were achieved for the paper produced using the cellulose pulp with a Kappa number of 46.6. The optical properties of this product varied significantly with the delignification degree of the wood pulp. Above a Kappa number of 47, the crucial strength indicators show a downward trend. Therefore, it can be concluded that the wood pulp with a Kappa number of 46.6 exhibited optimal utility properties. This result is in accordance with the discussion above; i.e., papers made from high-yield pulp, as well as those produced via the addition of relatively high quantities of chemicals, have lower strength indices. In the high-Kappa-number range, the strength properties decreased due to increased lignin content, which leads to stiffening of the fibres. At Kappa numbers below 47, the decline in paper strength was related to cellulose degradation, that is, a reduction in the degree of cellulose polymerisation, which has a significant impact on its mechanical durability.

In order to select the optimal degree of pulp delignification in terms of pulp efficiency, refining time, and paper strength properties, the area of paper that could be obtained from 1 ton of wood was calculated for all the analysed pulps; for comparison, these values were calculated for papers with the same strength properties as the optimum experimentally obtained paper (Tables 3 and 4).

Table 3. Paper area obtained from 1 ton of wood with a tensile strength of 7647 N/m corresponding to pulp with a Kappa number of 46.6.

Kappa Number	Tensile Index	Grammage	Pulp Yield	Area of Paper Produced from 1 Metric Ton of Wood
	[N·m/g]	[g/m^2]	[%]	[m^2]
89.7	8.33	91.8	47.2	5143
76.5	8.85	86.4	46.9	5427
63.8	9.40	81.4	45.7	5617
46.6	9.56	80.0	43.5	5438
41.9	9.09	84.1	42.3	5027
35.2	8.12	94.2	41.2	4375
29.6	7.51	101.9	40.5	3976
26.9	7.28	105.1	39.4	3749
23.7	6.77	113.0	38.5	3408
19.1	6.36	120.2	36.9	3070

Table 4. Paper area obtained from 1 ton of wood with a tear resistance of 490 mN corresponding to pulp with Kappa number of 46.6.

Kappa Number	Tear Index	Grammage	Pulp Yield	Area of Paper Produced from 1 Metric Ton of Wood
	[mN·m^2/g]	[g/m^2]	[%]	[m^2]
89.7	5.25	93.3	47.2	5057
76.5	5.75	85.2	46.9	5504
63.8	6.00	81.7	45.7	5596
46.6	6.13	80.0	43.5	5438
41.9	5.88	83.4	42.3	5072
35.2	5.75	85.2	41.2	4835
29.6	5.81	84.3	40.5	4804
26.9	5.75	85.2	39.4	4623
23.7	5.75	85.2	38.5	4518
19.1	5.63	87.1	36.9	4236

Based on the paper for which the highest tensile index (9.56 N·m/g) was achieved, the tensile strengths of the other analysed pulps were calculated. Using the achieved tensile strength of 7647 N/m and tensile index values, the hypothetical paper density needed to achieve the same tensile index as the optimum experimentally obtained paper was calculated for the pulps of various delignification degrees. Using this value and the efficiency of wood pulp extraction for each pulp, the area of paper with the desired tensile strength value that could be obtained from 1 ton of wood was calculated (Table 3). Analogous calculations were carried out using the tear index (6.13 mN·m^2/g). Using the achieved tear resistance of 490 mN and tear index values, the hypothetical paper density needed to achieve the same tear index as that of the optimum experimentally obtained paper was calculated for the pulps of various delignification degrees (Table 4). In both cases, the highest paper areas were obtained for the pulp with a Kappa number of 64. Thus, the production of pulp with a Kappa number of approximately 60 should be most favourable. This value is optimum in terms of both pulp yield and paper strength properties. Moreover, this pulp can be refined in a shorter time than pulp with an efficiency of 47.2% and Kappa number of 89.7 units. This indicates that this degree of pulp digestion allows not only obtaining the maximal amount of paper from a given quantity of wood but also a nearly 10% reduction in the energy consumption of the refining process.

Finally, in order to assess the advisability of increasing the Kappa number of cellulose pulps, a comparison of the technological and utility parameters of high-yield wood pulp with the highest Kappa number (89.7) and the wood pulp with the optimal Kappa number (63.4) was conducted. The parameters of the wood pulp with a Kappa number equal to 63.4 were chosen as a reference for the evaluation of the pulp with a Kappa number of 89.7 based on the analyses above.

The results shown in the Table 5 indicate that the major advantages of increasing the Kappa number of the wood pulp are the 3.3% increase in the cellulosic pulp yield of the wood and the 9% decrease in chemical consumption. However, these positive effects are offset by the 9% poorer beatability, 11% lower brightness, 210% greater shive content, 4–12% lower paper strength properties, and 9% reduction in paper area for the obtained high-yield wood pulp. Based on the savings derived from the reduction in the cost of high-yield wood pulp and the additional costs associated with energy consumption during refining, an attempt can be made to identify paper products for which the replacement of standard cellulose pulp with increased efficiency paper pulp would be expedient.

Table 5. Comparison of the parameters of selected cellulosic pulps.

Parameter	Pulp with a Kappa Number of 89.7	Pulp with a Kappa Number of 63.4	Percentage Difference
Yield of pulp [%]	47.2	45.7	3.3
Shives content [%]	3.10	1.00	210
Active alkali addition [%]	20	22	9
Beatability of pulp [s]	6.0	5.5	9
Tensile index [N·m/g]	8.33	9.40	11
Tear index [mN·m^2/g]	5.25	6.00	12
Burst index [kPa·m^2/g]	6.75	7.00	3.6
Brightness [%]	16	18	11
Area of paper produced from 1 metric ton of wood [m^2]	5057	5596	9.6

4. Conclusions

From the results of the tests conducted in this study, pulp with a Kappa number equal to 64 was determined to be optimum based on the pulp yield and properties, as well as the expected costs associated with the pulp refining time and the quantity of raw material needed to obtain paper with desirable properties. Given the high product properties of the produced paper, which are critical to the market value and user satisfaction for paper-based materials, the economic legitimacy of the production of fibrous pulps of increased Kappa number should be considered. In order to implement such manufacturing on a broad scale, a technology that can simultaneously achieve high paper strength properties, high brightness, and reduced energy consumption in the pulp refining process must be developed. Thus, the optimisation of paper production processes must consider chemical, energy, and water economy, which are critical for the minimisation of the environmental impact of paper product manufacture. The fibrous pulp digestion process and the optimal Kappa number value should therefore be paid particular attention, as these represent key challenges in the development of economically and ecologically justifiable timber pulp manufacture processes.

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