Ciência Florestal
ISSN 1980-5098
OPEN ACCESS
Ci. Fl., Santa Maria, v. 34, n. 3, e85566, p. 1-20, July/Sept. 2024 • https://doi.org/10.5902/1980509885566
Submitted: 30th/10/2023 • Approved: 15th/02/2024 • Published: 26th/07/2024

Review Article

Influence of basic density and chemical composition of wood for the pulp industry: a case study

Influência da densidade básica e da composição química da madeira para a indústria de polpa celulósica: um estudo de caso

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ABSTRACT

The *Eucalyptus* and *Pinus* genera represent the main wood species which form the planted forests used by the pulp and paper sector in Brazil, and so many studies are conducted correlating the wood technological characteristics, the pulping process variables, and the pulp quality. The objective of this study was to perform a bibliographic review on studies that relate the basic density and chemical composition of wood with the pulping process variables and the pulp characteristics. The exploratory study principle was implemented through a literature review. The main studies found in this review showed that the best *Eucalyptus* clones used in the pulp industry had a basic density between 400 and 550 kg.m^{-3}, unbleached pulp yield between 45 and 55%, kappa number 17-18, and brown pulp viscosity greater than 1200 g.cm^{-3}. The best *Pinus* clones presented basic density varying between 370 and 440 kg.m^{-3}, lower than the variation observed for *Eucalyptus*; a similar pulp yield to studies with *Eucalyptus*, varying between 45 and 51%; and kappa number 30-32, higher than that used in cooking with *Eucalyptus* wood. The results obtained in this work allowed to conclude that basic density was the most used wood characteristic in the pulp industries to guide the process yield, while the extractive content and the ratio of syringyl (S) and guaiacyl (G) units in lignin (S/G ratio) were little presented in research.

Keywords: Wood quality; *Eucalyptus*; *Pinus*; Cellulose

RESUMO

Os gêneros *Eucalyptus* e *Pinus* representam as principais espécies madeireiras que formam as florestas plantadas utilizadas pelo setor de celulose no Brasil, e por isso muitos estudos são realizados correlacionando as características tecnológicas da madeira, as variáveis do processo de polpação e a qualidade da polpa celulósica. O objetivo deste trabalho foi realizar uma revisão bibliográfica sobre os estudos que relacionam a densidade básica e a composição química da madeira com as variáveis de processo de polpação e com as características da polpa celulósica. Foi utilizado o princípio do estudo exploratório por meio de uma revisão de literatura. Os principais estudos utilizados nesta pesquisa apontaram que os melhores clones de eucalipto utilizados na indústria de polpa apresentaram densidade básica entre 400 e 550 kg/m³ , rendimento em polpa não branqueada entre 45 e 55%, número kappa 17-18 e viscosidade da polpa marrom superior a 1200 cm³/g. Com relação aos melhores clones do gênero *Pinus*, estes apresentaram densidade básica variando entre 370 e 440 kg/m³ , menor que a variação verificada para o *Eucalyptus*; rendimento similar aos estudos com *Eucalyptus*, variando entre 45 e 51%; e número kappa 30-32, maior que o utilizado em cozimentos com madeira de *Eucalyptus*. Os resultados obtidos neste trabalho permitiram concluir que, dentre as características da madeira, a densidade básica foi a mais utilizada nas indústrias de celulose para nortear o rendimento do processo, enquanto o teor de extrativos e relação S/G da lignina foi pouco apresentada pelas pesquisas.

Palavras-chave: Qualidade da madeira; *Eucalyptus*; *Pinus*; Celulose

1 INTRODUCTION

According to the Indústria Brasileira de Árvores (IBÁ, 2023), Brazil has an area of 9.94 million hectares with commercial tree plantations, and is considered a global reference country when it comes to productivity, with *Eucalyptus* being 7.6 million ha.year and *Pinus* 1.9 million ha.year. As a comparative advantage for forestry production, Brazil has favorable soil and climate conditions that encourage the forestry sector to invest in research and development of the best forestry techniques, improvement and forest management, as well as in sustainable industrial practices.

The main woods used by the pulp and paper sector in Brazil belong to the *Eucalyptus* and *Pinus* genera, and represent 75.8% and 19.4%, respectively, of the total area of planted trees. Cellulosic pulp from these woods represents 59% of exported products, which is why Brazil was considered the second largest producer and largest exporter of cellulose on the world market in 2021 (IBÁ, 2022).

In this scenario, wood is considered an economically important raw material for the pulp and paper sector due to its high cultivation, transport and processing costs, and which needs studies prior to its use for better process efficiency and greater use. As it is a heterogeneous product, different samples from the same tree may present significantly different technological properties (chemical, anatomical, physical and mechanical); as it is an anisotropic material, it presents different technological properties when considering its three observation planes; and it is hygroscopic because its humidity varies according to relative humidity and atmospheric temperature. These variations in wood have significant effects on the quality of the final products.

In this context, it is important to highlight that there is not just one technological characteristic to determine wood quality for pulp production, but rather a combination of physical (basic density) and chemical characteristics (cellulose content, hemicelluloses, lignins, extractives), for example, pointing out the strong relationship between these wood characteristics and the yield and quality of unbleached pulp (Morais, 2008). Basic density is used in most studies to express wood quality (Kollmann, 1959), as in addition to requiring simpler instrumentation for its determination, it has an influence on the product quality and expresses highly significant relationships with almost all other technological properties.

Even more specifically in relation to the pulping process, the chemical composition of the wood affects the consumption of chemical reagents in the digester, the screened yield and the solids content in the black liquor (Gouvêa *et al*., 2009); therefore, understanding the chemical nature of wood is essential to understand studies to improve pulping variables and the final product characteristics.

In view of the above, the main objective of this work was to perform a bibliographical review on the influence of the basic density and chemical composition of wood on the main pulping process variables and on the unbleached pulp characteristics.

2 METHOD

2.1 Research and selection of bibliographic material

This work followed the exploratory study principle through a literature review, developed from selecting materials published in the last 20 years between 2000 and 2021, consisting of scientific articles, dissertations and theses.

The material was collected from the following scientific journals: Revista Árvore, Scientia Forestalis, Ciência Florestal, Cerne; and repositories of theses and dissertations from the following universities: Universidade Federal do Espírito Santo (UFES), Universidade Federal de Lavras (UFLA), Universidade Federal de Viçosa (UFV) and Escola Superior de Agricultura Luiz de Queiroz (ESALQ), using the following keywords: wood quality, *Eucalyptus*, *Pinus* and cellulose.

Next, a reading/screening was performed considering publications which addressed the influence of the basic density and chemical composition of wood on the pulping process variables and on unbleached pulp characteristics as selection criteria.

At a third level of selection, works which specified *Eucalyptus* and *Pinus* genera clones/species were considered, with information on spacing, age and tree cultivation location, and that clearly presented the pulping, temperature, active alkali and sulfidity variables, which are the most common in factories or adopted in research at universities, as well as the yield characteristics, kappa number and viscosity of unbleached pulp.

2.2 Preparation of data sheets based on selected bibliographic material

The information extracted from the selected bibliographies was organized into Excel spreadsheets containing the most relevant information for this study, namely: i) plantations/stands: species/clones, age, spacing and location; ii) wood characteristics: basic density and chemical composition; iii) pulping process variables: total cooking time, active alkali, sulfidity; and iv) unbleached pulp characteristics: yield, kappa number and viscosity.

2.3 Relationships between wood quality, pulping process variables and unbleached cellulosic pulp characteristics

Mathematical correlations were established between all selected variables described in the previous item to discuss the results. The objective of these correlations was to verify effects and influences between wood quality, pulping process variables and the unbleached cellulosic pulp characteristics.

2.4 Comparison between the unbleached pulp characteristics and the pulping process variables

A comparative chart was created to better understand the relationship between the basic density and chemical composition of wood with the pulping process and the quality of unbleached pulp, containing three different cooking times considered extreme conditions: 140, 150 and 253 min. This comparison sought to understand under what conditions the alkaline load variable should be changed due to the variation in the basic density and chemical composition of the wood, as well as the impact of this combination on the unbleached pulp quality. This comparison was only performed for wood of the *Eucalyptus* genus due to the limited amount of information regarding wood of the *Pinus* genus.

3 DEVELOPMENT

3.1 Assessment of information on technological characterization of wood for pulp production

A total of 28 articles and 45 dissertations/theses were selected in the first stage of material selection. Then, 19 articles and 30 dissertations/theses were considered in the second and third stages with more careful selections, which in addition to the titles were actually studies with results and discussions related to wood quality (technological characterization) for unbleached pulp production.

Based on these 49 selected works, data were collected from 59 genetic materials (clones), among which 79.7% were related to the *Eucalyptus* genus (47 clones) and 20.3% belonged to the *Pinus* genus (12 clones), all of which were work related to unbleached pulp production.

An important fact observed was the lack of information about forestry plantations: the age of the clone, the spacing used in the plantations and the place of origin were not informed in 28%, 57% and 28% of the *Eucalyptus* studies, respectively; and in 17 %, 83% and 0% of *Pinus* studies, respectively.

Considering the plantation information of age, spacing and origin as important, only 45% of the studies on *Eucalyptus* plantations and 0% of the works on *Pinus* plantations presented all this information.

Regarding the lack of information, basic density and complete chemical composition, all *Eucalyptus* studies presented the basic density, total lignin, holocellulose and extractive contents. However, of these *Eucalyptus* studies, 64% did not present the cellulose and hemicellulose contents separately, and 36% did not present the S/G ratio of lignin. The *Pinus* wood quality in terms of basic density, total lignin content, holocellulose and extractives was reported in all studies. On the other hand, the cellulose and hemicellulose contents were not reported separately in any of the selected studies.

Considering the information on basic density and complete chemical composition as important for wood quality, only 30% of the *Eucalyptus* studies presented all the information, while none of the *Pinus* studies were complete. This demonstrates that greater investment is needed in carrying out wood quality analyzes to evaluate the pulping process and the pulp quality, especially in studies involving *Pinus* wood.

3.2 Influence of wood basic density on unbleached pulp quality

Based on this case study, the *Eucalyptus* pulp yield varied between 47.3 and 57.6% for a basic density variation between 276 and 668 kg.m^{-3}, and the *Pinus* pulp yield varied between 44.2 and 50.7% for a basic density variation between 373 and 436 kg.m^{-3} (Figure 1A). It is noticeable that most of the basic density results observed in the best *Eucalyptus* clones for pulp production (in terms of yield) ranged between 400 and 550 kg.m^{-3}, higher than that observed for *Pinus* wood (373 and 436 kg.m^{-3}).

The unbleached pulp yield showed a tendency to remain constant with the variation of the basic density for *Eucalyptus* wood, as the operational conditions of the pulping processes are adjusted aiming at an objective kappa number (17-18) and a higher possible yield. However, the unbleached *Pinus* pulp yield showed a decreasing trend as the basic density of the wood increased; this signals the need for greater effort to delignify this wood as its density increases, and an explanation for the lower density of these woods in the pulp industry.

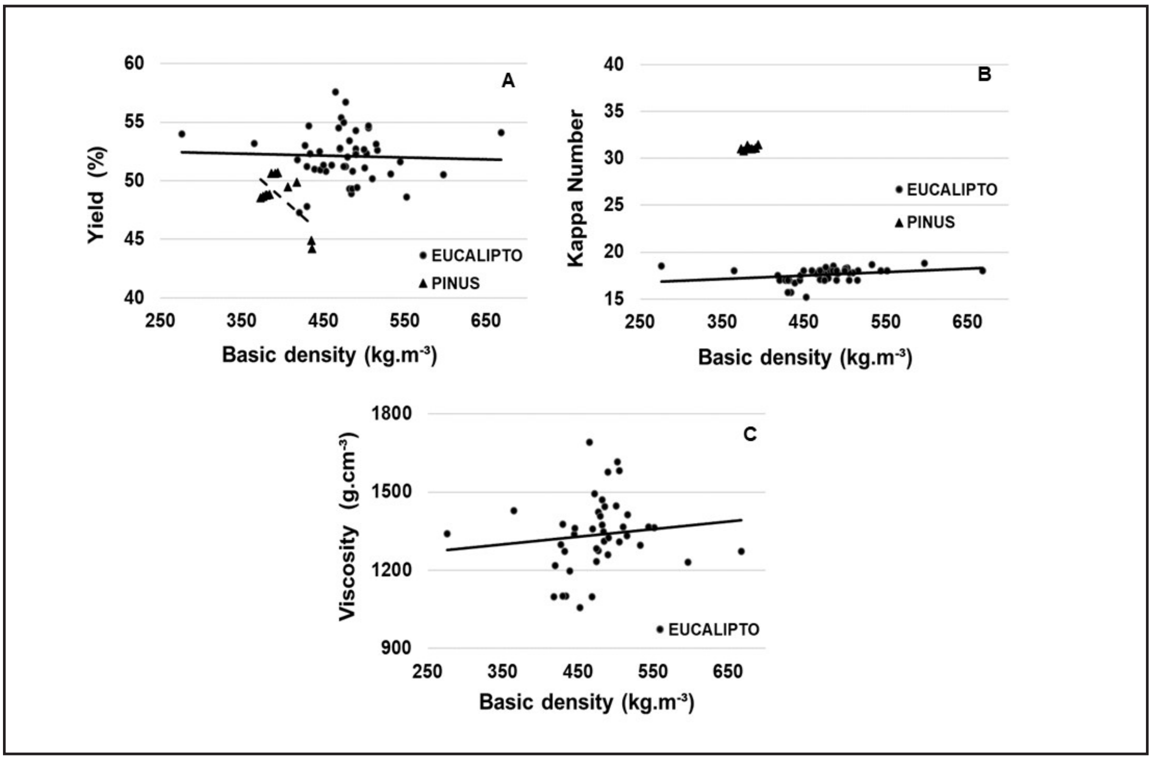
Despite the basic density of *Pinus* wood being lower than that of *Eucalyptus* wood, the unbleached pulp yield was similar, which shows that it is possible to achieve good yields from less dense wood, as long as the pulping process variables are properly adjusted and controlled.

Wood with high basic densities accompanied by high lignin contents has the effect of reducing the Kraft pulping process yield and increasing the kappa number considering the same pulping conditions (Medeiros Neto, 2012; Queiroz *et al*., 2004). These authors mentioned that this fact occurs due to the greater difficulty in impregnating higher density chips, which results in a greater demand for alkali during cooking, and consequently in a lower screened yield.

However, *Eucalyptus* wood with an average density between 450-550 kg.m^{-3} is recommended for use in the pulp industry (Santos, 2016), as it allows better cooking performance associated with lower specific wood consumption (Pereira *et al*., 2021).

The kappa number of the unbleached pulp increased with the increase in the basic density of the wood; it varied between 15.2 and 18.8 for the best *Eucalyptus* materials, and from 30.9 to 31.5 for the best *Pinus* materials, as shown in Figure 1B.

Figure 1 – Influence of wood basic density on the unbleached *Eucalyptus* and *Pinus* pulp yield (A); kappa number of unbleached *Eucalyptus* and *Pinus* pulp; and (B) viscosity of unbleached *Eucalyptus* pulp (C)



Source: Authors (2023)

The 17-18 kappa number range was the most observed in work related to short fiber pulp mills (*Eucalyptus*), in which denser woods are cooked at a higher kappa number, aiming to increase yield or preserve cellulose chains (higher viscosity). The kappa number observed for factories which operate with softwood fiber (*Pinus*) was around 30.

The choice of the kappa number in an industrial process does not only depend on the basic density of the wood, and factories vary the alkaline loads and other process variables (time, temperature and sulfidity) depending on the objective kappa number, meaning the degree of delignification of the unbleached pulp that is desired at the end of the process.

Santos (2018) explained that this occurs due to the presence of non-cellulosic fractions such as residual lignin, extractive content and hexenuronic acids that pulping was not able to solubilize, remaining in the cell wall of the fibers. Barbosa *et al*. (2008) stated that the amount of alkaline load that will be used is estimated through the basic density of the population, in addition to the yield.

Finally, *Eucalyptus* pulp showed a tendency for viscosity to increase as the basic density of the wood increased (Figure 1C). The viscosity variation was from 1055 to 1690 g.cm-^{3}, with the majority of values found in the range between 1200 and 1500 g.cm-^{3} for a basic density variation between 400 and 550 kg.m-^{3}.

Denser wood consumes more active alkali than those with low density and suffer greater degradation of carbohydrates, and in turn greater loss of viscosity (Mokfienski *et al*., 2008; Queiroz *et al*., 2004). However, in the high alkaline conditions necessary for cooking higher density wood, the greater degradation/solubilization suffered by hemicelluloses (carbohydrates with lower molecular weight) justifies the increased viscosity behavior, despite the greater degradation suffered by the fibers (Demuner, 2014).

Faced with this important discussion about the basic density of wood, cellulose factories have preferred to work with wood of medium to slightly high density in order to increase the productivity of digesters and increase the factory's daily production. In other words, the unbleached pulp quality can be adjusted within certain limits during the pulping process aiming at a greater daily digester production, which provides a lower specific wood consumption in the process.

3.3 Influence of the chemical composition of wood on unbleached cellulosic pulp quality

The chemical composition of wood has a strong influence on the pulping process and the unbleached pulp quality. The *Eucalyptus* pulp yields observed in this study were above 50%, as these were results from laboratory research with clones of industrial interest, while the *Pinus* pulp yield was slightly below 50%.

The pulp yield from *Eucalyptus* wood varied between 47.3 and 57.6%, with results above 50% due to the fact that the holocellulose content of the wood was above 55%, reaching 55% yield when the holocellulose content reached 70% (Figure 2A). On the other hand, the pulp yield decreased from 56.7 to 54.7% as the lignin content of the wood increased from 26.4 to 30.9% (Figure 2B), indicating the negative effect of this wood compound in *Eucalyptus* pulp yield.

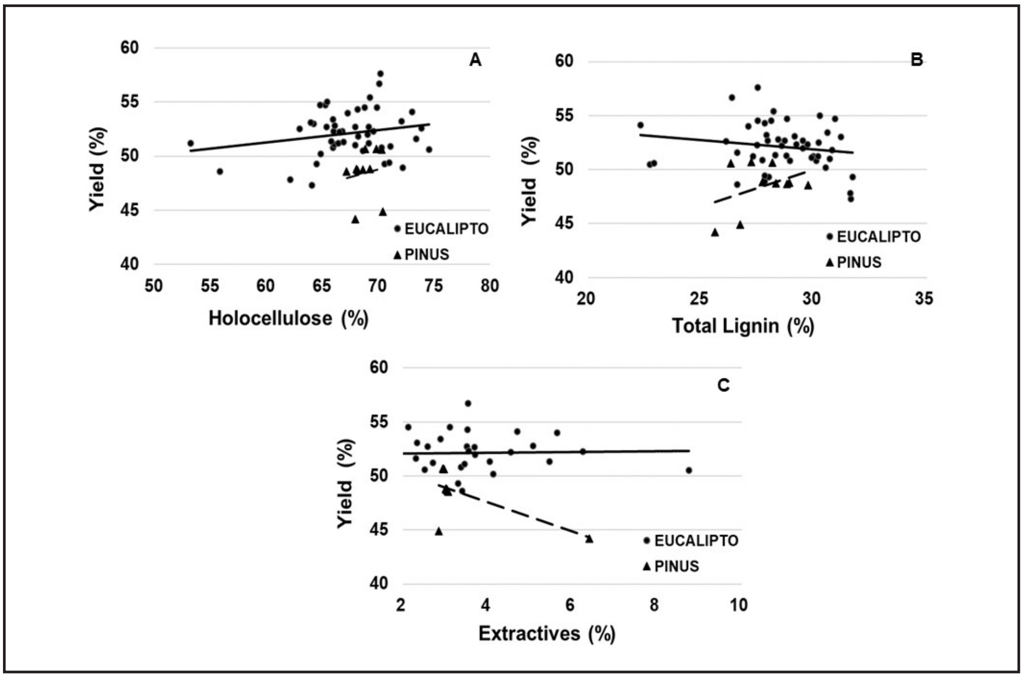
Regarding the extractive content of wood, no tendency to influence the yield of *Eucalyptus* pulp was observed, as they are woods which naturally have low extractive content, with values varying between 2.1 and 8.8%, in which the majority of values were concentrated between 2.1 and 4.1% (Figure 2C).

According to Segura (2015), a high holocellulose content positively affects the pulping yield. Perez (2002) concluded that the woods which had the highest screened yield values were those that had the lowest total lignin levels in the chemical composition of their wood.

Pulp yields close to 55% are characteristic of Kraft pulping processes of excellent quality *Eucalyptus* wood, with high holocellulose contents and low lignin contents (Segura, 2015), and low extractive contents (Duarte, 2007).

The pulp yield observed in *Pinus* wood varied from 44.2 to 50.7%, with an increase as the holocellulose content increased from 67.2 to 70.3%, which is the same behavior observed for *Eucalyptus* wood (Figure 2A). However, the unbleached pulp yield increased as the lignin content increased from 25.6 to 29.7%, being partly explained by the lower basic density of *Pinus* wood facilitating delignification, and by the lower delignification level, meaning the higher kappa number, observed in *Pinus* wood pulping studies, as shown in Figure 2B. Therefore, it is possible to infer that current clones with levels above 30% lignin can be considered less suitable, while materials with levels below 30% lignin are superior in quality for unbleached pulp production.

Figure 2 – Influence of the pulping yield with the chemical composition of *Eucalyptus* and *Pinus* wood: (A) holocellulose content; (B) total lignin content; and (C) extractive content



Source: Authors (2023)

In relation to the extractive content of *Pinus* wood, the *Pinus* pulp yield had a clear tendency to decrease as the extractive content increased in the wood, which is different from that observed for *Eucalyptus* wood, as shown in Figure 2C. The extractive content of the wood varied between 2.8-6.4% for a yield variation between 44.9-49.9%. Wood with a higher extractive content consumes more cooking and bleaching reagents and yields less pulp in the pulping process. This occurs because extractives cause a reduction in the brightness of bleached pulps and it is important to remove them prior to cooking and bleaching processes (Wehr, 1991; Duarte, 2007; Segura, 2012).

Wood with a lower extractive content, close to 2-3%, is considered to be of better quality, while those with an extractive content in the range of 5-8% are considered to be of lower quality. According to Segura (2012) and Alves (2010), extractives are one of the most undesirable components for the pulping process, as they negatively influence the consumption of reagents and the pulp yield, with the removal of the largest quantity of these wood constituents being favorable.

It is important to notice a smaller number of studies regarding the extractive content of wood for unbleached pulp production, especially when studying *Pinus* wood; although these woods theoretically have higher levels of extractives, works were found with materials that present a low amount of extractive content, around 2.8% (Vivian *et al*., 2015). On the other hand, the same was observed for *Eucalyptus* wood, which normally has low levels of extractives, but presented higher values, reaching 8.8% (Segura, 2015).

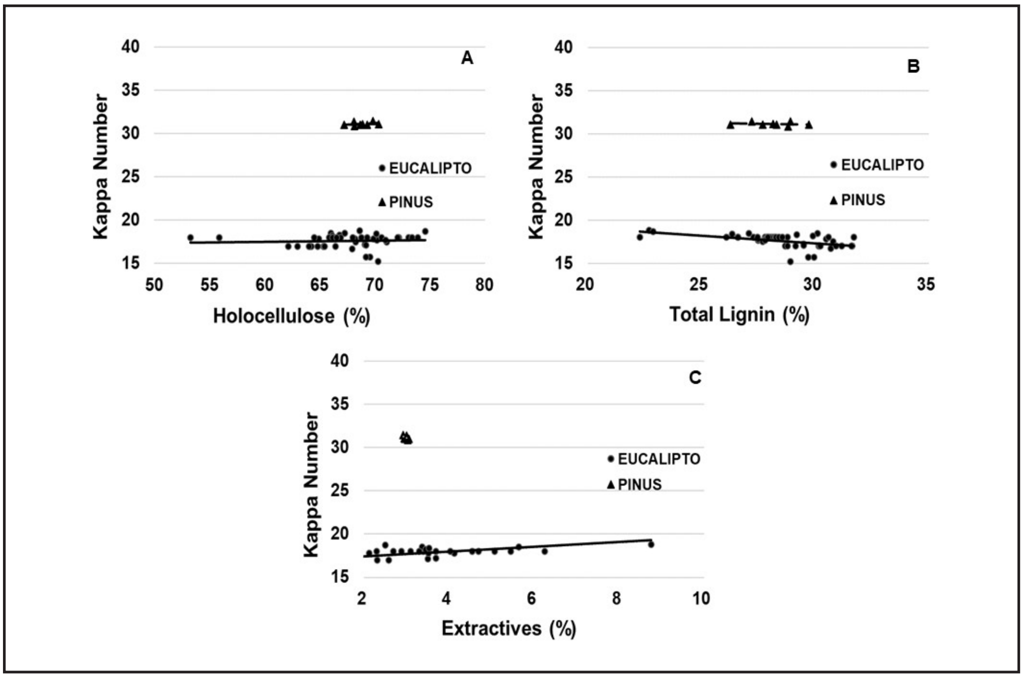
The kappa number of unbleached pulp indicates the degree of delignification imposed by the pulping process and varies depending on the wood or product to be manufactured. It was possible to perceive a clear relationship between the holocellulose content, total lignin content and extractive content of *Eucalyptus* and *Pinus* wood with the kappa number of the pulp, in which regardless of the chemical composition of the wood, the kappa number remained stable at 17.0-18.0 and 30.0-32.0, respectively (Figure 3A, Figure 3B and Figure 3C).

The objective kappa number of *Pinus* pulps (30-32) was higher than that observed in *Eucalyptus* pulps (17-18), precisely to avoid significantly compromising the process yield and the viscosity of the unbleached pulp, and is therefore considered an important control indicator of the pulping process.

This occurs because the wood is cooked with the previously defined objective kappa number based on a given degree of delignification, independent of the chemical composition of the wood and achieved by varying the alkaline load and other process variables, such as time, temperature and sulfidity.

The kappa number of unbleached pulp not only expresses the residual lignin after cooking, but also extractives and hexenuronic acids which compose the pulp after cooking. The higher the extractive content of the wood, the greater the chances of extractives in the unbleached pulp.

Figure 3 – Influence of the kappa number of the pulping process on the chemical composition of *Eucalyptus* and *Pinus* wood: (A) holocellulose content; (B) total lignin content; and (C) extractives content



Source: Authors (2023)

Cardoso (2002) explains that wood with a low lignin content requires a smaller amount of active alkali to delignify compared to wood with a high lignin content for the same kappa number of unbleached pulp.

Regarding the viscosity of the unbleached pulp, which is an indicator of the degradation suffered by the fibers during the pulping process, *Eucalyptus* pulps showed a tendency for viscosity to decrease as the holocellulose and total lignin contents of the wood increased (Figure 4A and Figure 4B, respectively), and with a reduction in extractive content (Figure 4C). The viscosity variation was from 1056 to 1690 g.cm^{-3} for a variation in holocellulose content between 53.3 and 74.6%, for a variation in lignin content between 22.3 and 31.7%, and for a variation in extractive content between 2.1 and 8.8%.

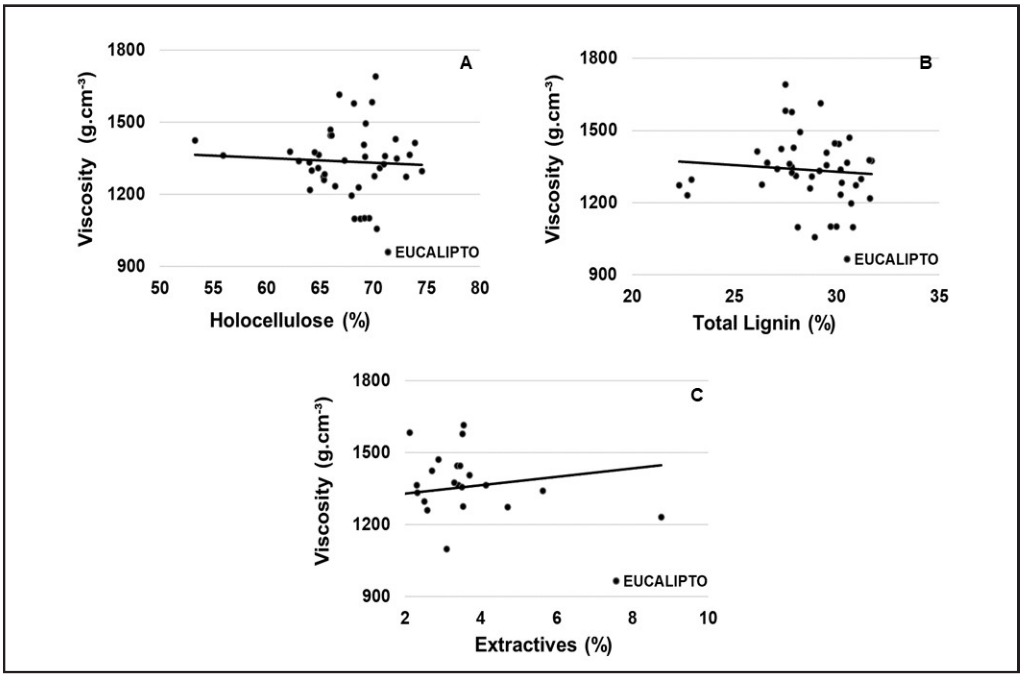
However, most viscosity values were concentrated in the following ranges: from 1376 to 1412 g.cm^{-3} for a holocellulose variation between 60 and 75%; from 1230 to

1690 g.cm-³ for a range of 26 to 31% lignin; from 1099 to 1614 g.cm-³ for a variation of 3.1 to 3.5% extractive content.

The slight reduction in the viscosity of the unbleached pulp can be explained by the increase in the holocellulose content of the wood, reflecting a greater presence of hemicelluloses (carbohydrates with a lower molecular weight); and the decrease in the total lignin content of wood as a consequence of greater fiber degradation (cellulose chains) caused by the need for greater delignification of wood, meaning greater use of cooking reagents and/or more severe cooking conditions (time and temperature).

Trugilho *et al*. (2004) evaluated the wood characteristics of 15 *Eucalyptus* spp. clones, as well as their performance in Kraft pulp production processes. These authors found clones with this inverse relationship between viscosity and holocellulose content. Some clones that presented the highest holocellulose contents (82.0% and 80.9%) also presented the lowest viscosities (1149 and 1177 g.cm-³), respectively.

Figure 4 – Influence of the pulping process viscosity on the chemical composition of *Eucalyptus* and *Pinus* wood: (A) holocellulose content; (B) total lignin content; and (C) extractive content



Source: Authors (2023)

Almeida and Silva (2001) highlighted that the extractive content present in wood directly influences the greater consumption of alkali. Therefore, a greater requirement for the amount of alkali implies greater degradation of carbohydrates, which can cause a drop in viscosity, being different from what was observed in this study.

Finally, no results were found in the literature consulted for this study relating the viscosities of *Pinus* unbleached pulps to the levels of holocellulose, total lignins and wood extractives.

3.4 Influences of pulping process parameters on the unbleached pulp quality

Pulping parameters are defined depending on the quality of unbleached pulp desired to meet the specifications of a given product. The information on *Eucalyptus* wood from the scientific materials used in this study to compare the pulping process parameters mostly indicated cooking times of 140, 150 and 235 minutes, sulfidity of 30% and active alkali of 17%, 19.6% and 21%.

From these data it was possible to observe that the cooking yield for *Eucalyptus* wood was higher when extreme conditions were used, meaning a shorter total cooking time (140 min) was associated with a lower load of active alkali (17%); and longer total cooking time (235 minutes) was associated with the higher alkali load (21%), as shown in Figure 5A.

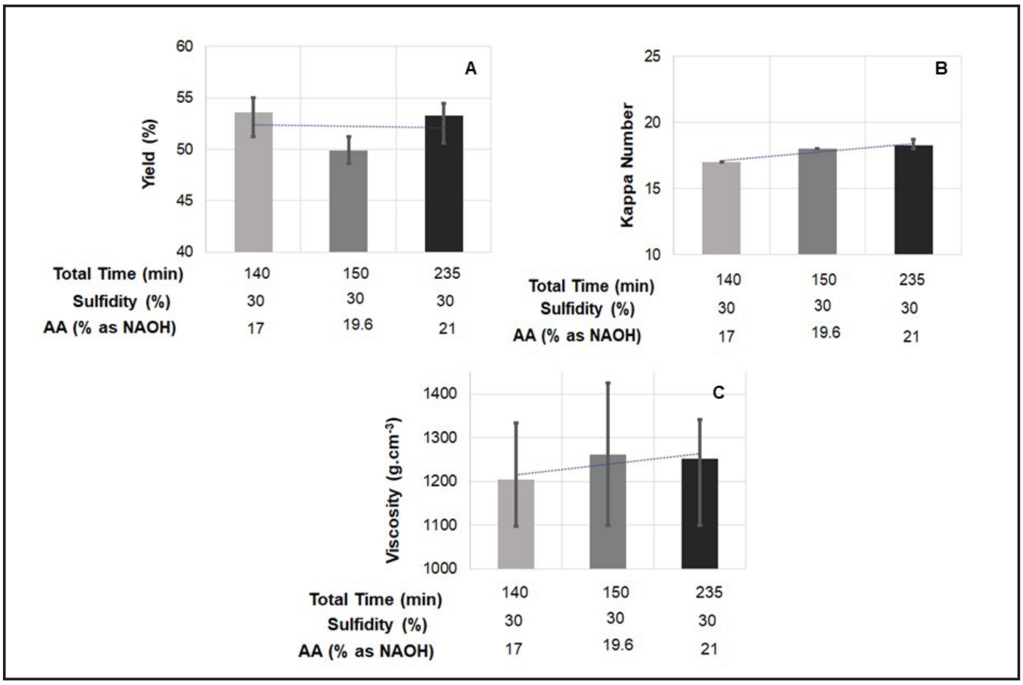
This demonstrates that even wood which is more difficult to delignify and easier wood can present good yields as long as these conditions are observed prior to cooking. On the other hand, the yield was lower when total cooking time and intermediate alkaline load were combined (150 minutes and 19.6%).

The kappa number was practically fixed for all combinations of time and temperature evaluated, varying in the small range between 17.0-18.7. However, a lower kappa number (17.0) was observed when the shorter cooking time and lower alkaline load (140 minutes and 17%) were combined, as shown in Figure 5B.

This happened because wood that requires more severe cooking conditions so as not to negatively affect the yield presented a slightly higher kappa number, which also helps with the unbleached pulp viscosity. On the other hand, the pulps that were easier to delignify had a lower alkali load and shorter cooking time, and consequently enabled greater deliginification at lower kappa numbers, with consequent lower viscosity due to this higher delignification level.

It was possible to notice and confirm that the unbleached pulp viscosity was higher when using the condition of average total time (150 minutes) and average active alkali (19.6%), or the condition of longer total time (235 minutes) and higher load of alkali (21%), a reflection of the pulp having a higher kappa number to maintain a good yield.

Figure 5 – Influence between: (A) pulping yield, (B) kappa number and (C) viscosity with pulping parameters (total time, sulfidity and active alkali) of *Eucalyptus* wood



Source: Authors (2023)

This higher viscosity under longer time and alkaline load conditions is influenced by the greater removal of hemicelluloses from the pulp, since these carbohydrates have lower molecular weight and are solubilized/degraded more quickly in the pulping process. On the other hand, viscosity was lower when associated with shorter cooking time and lower alkaline load (140 minutes and 17%), as shown in Figure 5C.

Thus, it was possible to infer that the unbleached pulp characteristics which resulted in greater productivity (yield) and quality (kappa number and viscosity) were obtained through combinations of pulping process parameters, meaning changes in the total time cooking and alkaline load variables influence the pulp productivity and quality.

4 CONCLUSIONS

The results obtained based on the search sources used in this study allowed us to conclude that:

– Greater investment is needed in conducting wood quality analyzes to evaluate the pulping process and the quality of unbleached pulp, especially in work involving *Pinus* wood;

– Basic density was the wood characteristic most frequently presented in scientific studies, as it has a good correlation with process yield;

– The extractive content and S/G ratio of lignin were the wood information least presented in the studies;

– The difference in the number of studies using *Pinus* wood in relation to *Eucalyptus* was noticeable, with the vast majority of studies focusing on Eucalyptus wood;

– The sulfidity of the process was a practically fixed variable (30%), while the total time and alkaline load varied according to the wood quality.

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How to quote this article

RAMOS, R. D.; LONGUE JUNIOR, D.; GOMES, F. J. B.; MEDEIROS, N. C. G. Influence of basic density and chemical composition of wood for the pulp industry: a case study. **Ciência Florestal**, Santa Maria, v. 34, n. 3, e85566, p. 1-20, 2024. DOI 10.5902/1980509885566. Available from: https://doi.org/10.5902/1980509885566. Accessed in: day month abbr. year.