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Article

Investigating the generation of wood wastes from mechanical processing of two forest species

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Abstract - The circular saw is a tool commonly used for wood processing. It may be presented at different models. Considering their specificities, they can generate different amount of waste. The objective of this study was to evaluate the generation of waste from *Tectona* grandis L. f. and *Pinus caribaea* var. *hondurensis*, processed with two saws of the multiple type (48 and 36 teeth) and one of the universal type (28 teeth). The cutting process followed in grain direction into ninety samples, 15 for each species and saw, until the sample was completely processed. The processing time was measured and the waste was collected in each operation. ANOVA and test of multiple comparison of averages were applied. The influence of the teeth number and type of saw on the amount of waste generated was verified. The universal saw was the one that generated the highest amount of waste. It reached up to 116% more than the multiple saw, that generated the lowest amount of waste (36 teeth). *P. caribaea* var. *hondurensis* generated 7% more waste and presented shorter processing time (22%), when compared to *T. grandis*.

Investigando a geração de resíduos do processamento mecânico da madeira de duas espécies florestais

Resumo - A serra circular é uma ferramenta comumente empregada para o processamento de madeira, sendo apresentada em diversos modelos e, por suas especificidades, podem interferir na quantidade de resíduos gerados. O objetivo deste estudo foi avaliar a geração de resíduos de *Tectona grandis* L. f. e *Pinus caribaea* var. *hondurensis*, processadas com duas serras do tipo múltipla (48 e 36 dentes) e uma do tipo universal (28 dentes). Foram efetuados cortes a favor da grã em noventa corpos de prova, 15 para cada espécie e serra, até o processamento completo da amostra. Foi medido o tempo de processamento e coletado o resíduo em cada operação. A ANOVA e o teste de comparação múltipla de médias foram aplicados. Constatou-se a influência do número de dentes e do tipo de serra na quantidade de resíduos gerados. A serra do tipo universal foi a que gerou maior quantidade média de resíduos, resultando em 116% a mais em comparação com a serra múltipla que gerou menor volume de resíduos (36 dentes). *P. caribaea* var. *hondurensis* gerou 7% mais resíduos e menor tempo de processamento (22%), quando comparado a *T. grandis*.

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Introduction

Wood is one of the products obtained from the forest that has the greatest diversity of uses, conferring a high contribution to the Brazilian national income. It can be used and reused in different segments and industrial stages, from furniture to energy generation. To obtain a final product, as the manufacture of furniture or sawn wood pieces for structural purposes, the raw material processing will be necessary, comprising steps that originate from the harvesting of the tree, through the secondary machining or wood processing (Melo et al., 2015, 2016). The last stage is machining, which is related to cutting wood using specific tools, aiming at product quality, minimum waste and operator safety (Silva et al., 2015).

Understanding the factors involved in the processing of a given species economically influences the production (Nascimento et al., 2017), reducing losses and improving the superficial surface of the material, thus generating greater use and added final value to the product (Lopes et al., 2014). Several factors influence the generate amount of waste, as the machining operations (Latorraca et al., 2015). The factors inherent to wood range from the structure variability (Melo et al., 2015) among species and individuals to be machined, such as their age, specific density, grain, moisture, hardness, knots presence, growth stresses (Silva et al., 2015), log taper and curvature (Nassur et al., 2013). Moreover, external factors, such as operator training, operating conditions of machines and cutting tools, and variables of the equipments and process, such as cut thickness, number and height of teeth, orientation and speed cutting of the wood against the cutting tool may also influence the generate amount of waste (Costes et al., 2004; Silva et al., 2015).

In some wood segments, the waste generated when sawing a log can vary from 40 to 70% (Garcia et al., 2012; Monteiro et al., 2013, 2017) and decisions about the optimum utilization of logs and the wood processing can lead to an increase of 10% to 25% in the yield of processed wood (Valério et al., 2007). The equipment usually used in local wood industries may be responsible for a large amount and diversity of waste (Brasil, 2009; PIMADS, 2013).

According to Louzada Júnior et al. (2017), the tree planted sector in Brazil generated in 2016, approximately, 48 million tons of solid waste. The main generating sources were forestry activities, with approximately 33.7 million tons (70.5%) of waste and industrial activities, which generated 14.1 million tons (29.5%). The largest amount of waste generated comes from the primary and secondary log processes; the circular saw is the main equipment in the waste generation (Fagundes, 2003, 2006; Ugulino et al., 2017). The circular saw is frequently present in the wood processing units, with a variety of types, which vary in dimensions and in the cutting teeth number (Krilek et al., 2014). Regarding the circular saw, it is highlighted that the choice and composition of the material, shape and teeth number, as well as the cutting angles, vary with the type of operation and with the nature of the material to be sawed (Çakmak & Malkoçoğlu, 2019).

Due to their varied architectures, the types of circular saw blades interfere with the waste generated amount during wood processing (Nasir & Cool, 2020). The most frequently studied factors are: number of teeth, angles, cutting edge, lateral clearance, manufacturing material and cutting speed (Davim, 2013). In addition, other factors are also considered, such as: the species (physical, mechanical properties and wood anatomical characteristics) (Nasir & Cool, 2020), the tool wear and tear (Porankiewicz et al., 2016), the required cutting power (Kminiak & Kubł, 2016) and the surface quality of the processed wood (Kminiak & Gaff, 2015), among others.

The knowledge of the waste generated due to the machinery present in wood processing units contributes to the management and quality control, uniformity of processes, minimization and possible use of the waste as raw material for combustion and thermal energy (Dias Júnior et al., 2014) or for compaction (briquetting and pelletizing) (Kelyounssi & Halim, 2014). The type of saw blade and number of teeth can lead to different amounts and formats of waste, and consequently they may have different destinations, such as bioenergy, fillers, gardening, among others.

In 2019, the total area of planted forests in Brazil was 9 million ha, mainly represented by *Eucalyptus* spp., *Pinus* spp., and *Tectona grandis*, the exotic species with major planted area (IBÁ, 2020). These forests contribute for the wood supply for different industrial segments and the environment protection (Araújo et al., 2017). *T. grandis* presents rapid growth, high economic value, resistance to pests, and competitive commercial value due to wood properties. It is one of the most valued species in the world (Schuhli & Paludzyszyn Filho, 2010; Camino & Morales, 2013; Silva et al., 2016).

The plantation of *P. caribaea* var. *hondurensis* in Brazil has been successful, due to the ability of the species to stablish in tropical regions, with low occurrence of frosts and water deficit (Shimizu, 2008; Sebbenn et al., 2010; Santos et al., 2016). The genetic breeding of the species increased the production of wood and resin, mainly for solid wood, long-fiber pulp and paper industries, and resin sector (Santos et al., 2016).

The objective of this research was to investigate the influence of the circular saw blades types on the generation of wastes from the mechanical processing of wood from two forest species.

Material and methods

Three trees of *Tectona grandis* L.f. and *Pinus caribaea* var. *hondurensis*, all with twenty years old, were harvested in an experimental stand of the Federal Rural University of Rio de Janeiro (UFRRJ) in Seropédica, Rio de Janeiro State, Brazil (22°45’ S 43°41’ W, and at 38 m above sea level).

We used only the first log of each tree (2.20 m in length). The first step was the log conversion into boards. The procedure was carried out using a portable horizontal saw (3.0 HP 220/380 V three-phase motor, cutting length of 2000 mm, and main saw rotation of 4,200 rpm). After this stage, the boards underwent the drying process in open air for one month. When the moisture achieved lower values than the fiber saturation point (FSP), the samples were produced using table saw with a 2000 mm inclined axis. The samples had 10 cm x 10 cm x 2.5 cm (length x width x thickness), and they were used for the subsequent tests, following an adaptation of the ASTM D1666 standard (ASTM, 2011) (Figure 1).

Machining and quantification of the generated waste

The wood processing was carried out in favor of the grain in ninety samples, 15 for each species. The saw was conducted until the sample was completely processed. Machining was carried out in favor of the grain, in the same table saw equipment described previously. The engine generates a power of 2.2 kW, extrapolating to 40 h of work per week in a laboratory sawmill, and it is estimated 88.26 kW h^{-1}. The wood waste mass amount

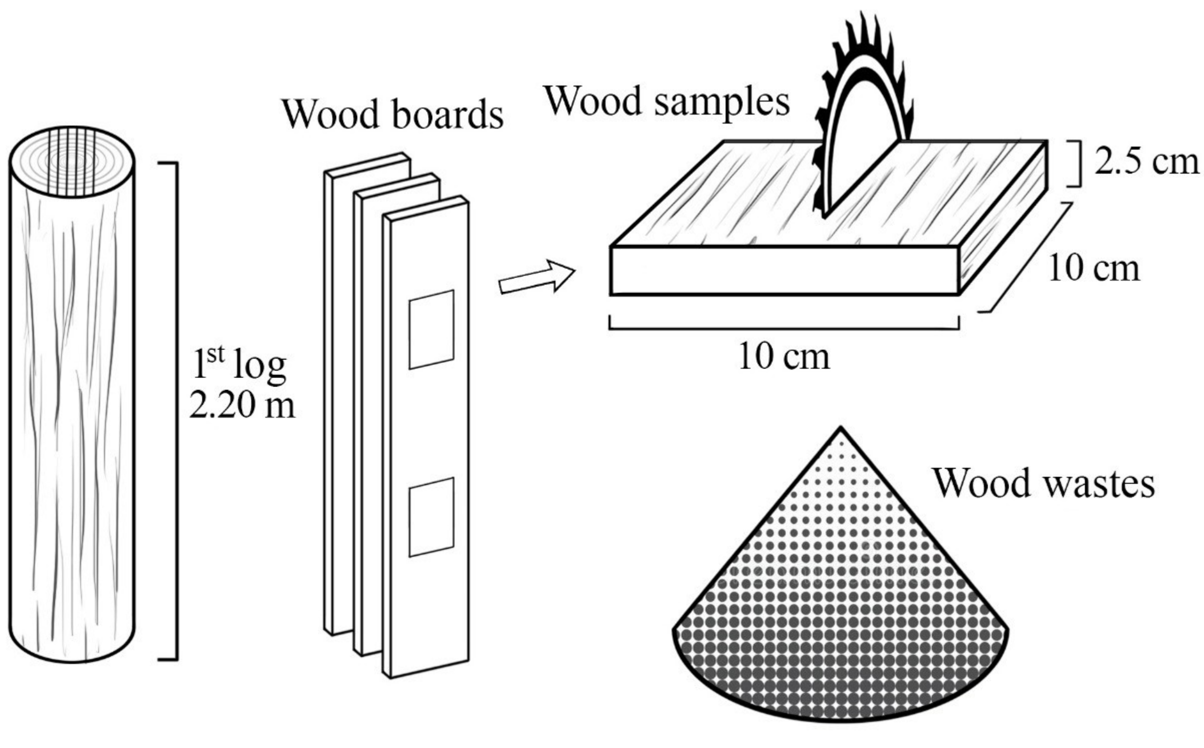

Figure 1. Scheme of the boards, wood samples and waste generated from the first log of tree species.

at the end of the processing day was estimated based on an eight-hour working day, and the volume of the samples were tested (0.0125 m³). We used three circular saw blades with different characteristics (Table 1 and Figure 2). Saw blades, or also called saw discs, 1 and 2 are considered multiple type saws and saw blade 3 is a universal type blade. It is important to mention that the saw blade number 3 presented an anti-kickback shoulder, and all the studied saw blades presented positive hook angle.

Machining was conducted and timed with the aid of a chronometer, counting the cut time for each sample. The cuts were in the longitudinal direction of the samples, parallel to the wood fibers. The cutting time in the machining operation performed in this research can be defined by the time required for each saw blade to pass through the sample completely, separating it into two parts. The sawdust was collected at the main outlet of the circular saw. It was identified and weighted using a precision analytical balance with 0.001g accuracy. The wood basic density was analyzed according to the NBR 7190 standard (ABNT, 1997).

Table 1. Characteristics of the three studied saw blades.

Saw	Diameter (mm)	Teeth number	Plate Thickness (mm)	Kerf (mm)	Top clearance angle	Hook angle
S1	450	48	3,90	4,65	14º	13º
S2	200	36	1,70	2,65	8º	17º
S3	400	28	2,85	3,80	15º	13º

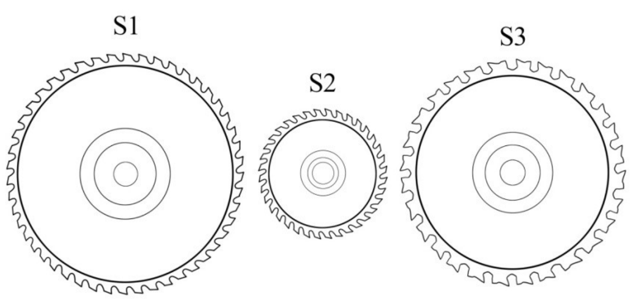

Figure 2. Saw blades used in the tests: (S1): 48-tooth saw blade; (S2): 36-tooth saw blade and (S3): 28-tooth saw blade.

Data analysis

The research followed a completely randomized design in a 2 x 3 factorial scheme, totaling six treatments: two species and three types of saw blades (S1 - 48 teeth, S2 - 36 teeth, and S3 - 28 teeth), with fifteen repetitions each. The processing time was measured with a chronometer, the sawdust weight was measured after each cutting process, and yield process were calculated. Data normality, homogeneity of variances and absence of autocorrelation of errors were analyzed and verified before the analysis of variance (ANOVA). The Tukey test, at 95% probability level, was performed using R software version 3.4.1 (R Development Core Team, 2009).

Descriptive analysis was performed calculating the average of the wood waste generated for each saw blade and species and for the processing time of each species. From the averages, the increase or decrease (in percentage) of the generation of waste and processing time between the species and the saw blades studied was analyzed.

Results

We observed that the smallest teeth number, when comparing the same type of blade (multiple saw - S1 and S2) resulted in lower waste amounts (Table 2). An increase of 28% (S1) and 116% (S2) was observed in the average generation of waste, when compared with universal saw blade (S3).

The wood moisture content was lower than the fiber saturation poin (FSP) for both species (≈ 14%), and *Tectona grandis* and *Pinus caribaea* var. *hondurensis* presented basic density equals to 0.55 g cm^{-3} and 0.49 g cm^{-3}, respectively.

The wood processing with smaller plate thickness saw blade (S2) originated the lower amount of waste. It is important to mention that there was no difference in the granulometry of the sawdust obtained through processing with different saw blades. The blade with the lowest number of teeth (universal saw - S3), but with a different architecture from the others (presence of an anti-kickback shoulder), generated the highest amount of wood waste.

The time spent to process the samples of the two species studied using the three circular saw blades is presented in Table 3.

The processing time in absolute terms was longer for *T. grandis* wood when compared to the processing of *P. caribaea* var. *hondurensis*. The processing time suffered the effect of the saw blade teeth number, showing inverse and asymptotic behaviors (Table 2). For instance, the average time decreased from saw blade S3 (28 teeth) to S2 (36 teeth) and increased from S2 to S1 (from the highest to the lowest number of cutting teeth) when processing the wood of *T. grandis*.

The amount of generated waste by the number of teeth on the saw blades varied. In general, *P. caribaea* var. *hondurensis* wood presented a higher generation of waste, when compared to *T. grandis* wood (Table 4).

Table 2. Average waste produced by the processing of wood in different circular saw blades.

Species	Waste generated mass (g)			
	Saw 1 (48 teeth)	**Saw 2 (36 teeth)**	**Saw 3 (28 teeth)**	**Mean**
Tectona grandis	4.76 ^{bB} (± 0,04)	3.77 ^{cA} (± 0,04)	7.33 ^{aA} (± 0,04)	5.29
Pinus caribaea var. *hondurensis*	6.72 ^{bA} (± 0,02)	3.02 ^{cB} (± 0,17)	7.32 ^{aA} (± 0,09)	5.69
Mean	5,74	3,40	7,33	

Values in parentheses = standard deviation. Averages followed by the same lowercase letters in the line and uppercase letters in the column do not differ statistically by Tukey test ($p \geq 0.05$).

Table 3. Time for wood processing of the studied species.

Species	Processing time (s)			Mean
	Saw 1 (48 teeth)	**Saw 2 (36 teeth)**	**Saw 3 (28 teeth)**	
Tectona grandis	1.90 ^{aA} (± 0,53)	1.83 ^{aA} (± 0,37)	2.43 ^{aA} (± 0,64)	2.05
Pinus caribaea var. *hondurensis*	1.62 ^{aA}(± 0,29)	1.67 ^{aA} (± 0,27)	1.51 ^{aB} (± 0,25)	1.60

Values in parentheses = standard deviation. Averages followed by the same lowercase letters in the line and uppercase letter in the column do not differ statistically by Tukey test ($p \geq 0.05$).

Table 4. Estimated mass of waste generated per day from wood processing.

Species	Mass of waste generated (kg day^{-1})		
	Saw 1 (48 teeth)	**Saw 2 (36 teeth)**	**Saw 3 (28 teeth)**
Tectona grandis	72.0	59.5	86.6
Pinus caribaea var. *hondurensis*	119.2	51.6	139.4

Discussion

The characteristics of the saw blade directly influenced the yield and consequently influenced the amount of waste generated for the two processed species (Table 1). This was also observed by Gonçalves (2001) and Fagundes (2003, 2006). It is possible to affirm that the decrease in the number of teeth in the multiple saw blade (from 48 to 36 teeth) resulted in a tendency to decrease the amount of waste generated. However, it is important to highlight the difference between the saw blade thickness. When using a universal saw with smaller number of teeth (28 teeth), the amount of waste did not decrease. In a study comparing teeth models for band saws, Carmo et al. (2014) pointed out that the geometry of the teeth affected the amount of waste generated. Thus, the observed results may be justified due to the fact that the 28-tooth saw blade has a different hook angle in addition to alternating teeth and a larger diameter saw blade (Çakmak & Malkoçoğlu, 2019). The geometry and alternating shape, related to the presence of anti-kickback shoulder, of this saw blade result in a larger retention surface, which causes a longer contact and processing time between the saw and the sample, generating a greater waste mass amount when compared to the other studied saws blades. It is evident that the generation of waste is influenced not only by the teeth number on the saw blade, but also by cutting angle, saw diameter and tooth arrangement.

The teeth number is one factor that influences the wastes generation, with the saw blades alternately, considering that a smaller teeth number is responsible for the greater obtained amount. However, such waste generation still depends on other variables such as the diameter, thickness, hook angles (being negative or positive), material of the saw blade, cutting orientation (for or against the grain), density and moisture of the wood and cutting speed. When cutting against the grain direction, the number of teeth must be greater and the diameter of the gullet and bore must be lower. When cutting in favor of the grain, as carried out in this research, the diameter of the saw blade must be larger and the hook angle must be smaller (Çakmak & Malkoçoğlu, 2019).

The 28-tooth (universal) saw, which had the highest amount of waste generated, presented no significant difference between *Tectona grandis* and *Pinus caribaea* var. *hondurensis*, possibly due to the saw blade shape and its characteristics, as teeth number diameter, thickness, and angles. The plate thickness and shape of the teeth were different, with a greater hook angle, and the space between the tooth also presented a different shape when compared to the others. As a result, there was a load on the front, rounded and rear surfaces of the cutting angle, thus creating greater resistance (Krilek et al., 2014) and consuming more energy. The use of this type of saw can cause loss of raw material to be processed, due to the shape of the teeth, consequently generating an unwanted increase in the amount of waste, and wood wastes for processing industries.

For multiple saw blades, it was possible to verify a significant difference between the saw with 48 teeth saw blade (S1) and 36 teeth saw blade (S2). It was evident that the amount of waste generated is influenced not only to the characteristics of the machinery, but also to factors inherent to each species, highlighting the difference between hardwood and softwood, as anatomy and chemical composition.

T. grandis showed a reduction in processing time when using a multiple saw with a smaller number of teeth, while for *P. caribaea* var. *hondurensis* the lowest time spent for processing occurred using the universal saw. This behavior shows that the type of disc affects the amount of waste proportionally regardless of the species, as both species had the lowest and highest wastes generation with the use of the same saws. However, in relation to time, there is an influence of the characteristics inherent to each species, making possible to assess which is the best blade to obtain the least amount of waste.

T. grandis presents a basic density value of 0.52 - 0.64 g cm^{-3} (Bonduelle et al., 2015; Garcia & Marinonio, 2016; Rizanti et al., 2018) and *P. caribaea* var. *hondurensis*, from 0.41 - 0.51 g cm^{-3} (Vale et al., 2009; Amorim et al., 2013; Trianoski et al., 2013; Gonçalez et al., 2018). It is inferred that this variable had an influence on the time required to perform the samples processing. In this study, the highest wood density species required more processing time (Table 3).

The lignocellulosic biomass from wood waste can be densified and applied in the generation of inputs for bioenergy through the manufacture of briquettes and pellets (Silva et al., 2017). Extrapolating to larger sawmills, ABIMCI (2009) estimated a production of 36,000 m^3 $year^{-1}$ of sawdust. If converted in energy, it would be possible to generate from 10,800 to 13,200 $MWh.year^{-1}$. Thus, the energy required for its operation could come from its own waste, being a fundamental aspect for the sustainable industry management (Monteiro et al., 2017).

However, it may vary according to the species. The resiniferous channels of *Pinus* sp. directly influence their suitability to be used as a heat source (Vissotto et al., 2015). Moreover, sawdust from *T. grandis* can be used in the industrial sector as an adsorbent (Nascimento et al., 2016; Mashkoor et al., 2018), use in briquetting processes (Faisal et al., 2021) and production of activated carbon (Saputro et al., 2017; Cansado et al., 2018).

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Conclusions

The generation of waste is influenced not only by the teeth number on the saw blade, but also by cutting angle, saw diameter and tooth arrangement.

The choice of the disc is strictly related to the type of species, softwood or hardwood, which will be processed.

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