MICRO-CHIPPING FOREST RESIDUES: AN EVALUATION OF FEEDSTOCK QUALITY, PRODUCTIVITY AND COST

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Feedstock Development

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Micro-chipping forest residues: an evaluation of feedstock quality, productivity and cost

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Abstract:

Forest residues generated from timber harvest or thinning operations are a potential source of woody biomass for various bioenergy and bioproducts. New emerging in-woods biomass conversion technologies, such as torrefaction or briquetting, require specific feedstock characteristics to improve operational efficiencies. Meeting these feedstock specifications with mobile, high production, comminution machines is becoming a new challenge for biomass feedstock producers. This study evaluates the size distribution, moisture content, bulk density, and ash content of particles generated from micro-chipping stem wood that was separated from forest residues. Four material types: processed and unprocessed, softwood and hardwood stems were produced, air-dried, and chipped in-woods using a 12-knife, 570-kW drum micro-chipper. The average moisture content for the four material types ranged between 18 and 23%. Unprocessed hardwood and softwood produced micro-chips with the longest (6.45 mm) and shortest (4.28 mm) geometric mean particle length, respectively. The bulk density of the four material types ranged from 226.82 – 299.53 kg/m^3. Ash content ranged from 0.25 and 1.18%. The chipper produced 34.0 BDmT of micro-chips per productive machine hour at a cost of \$10.38/BDmT while consuming 2.66 liters of diesel per BDmT. The productivity, fuel consumption, and operating costs were similar to other high production chipping and grinding machines reported in the literature. The primary difference and advantage of using a micro-chipper was the size of chips produced, which can meet certain feedstock specifications and improve transportation by having a greater bulk density.

Keywords:
Woody biomass feedstock; particle-size distribution; moisture content; bulk density; ash content, biomass conversion technologies

1. Introduction

Comminuting forest residues generated from timber harvest and fuel reduction thinning operations is an integral part of preparing a feedstock for emerging in-woods biomass conversion technologies (BCT), such as torrefaction, pyrolysis or densification. Typical options for comminution include grinding and chipping. Most grinders have the advantage of being able to accept materials that are highly variable in shape and size, and contaminated with rock and dirt (e.g., stumps and branches). However, research has shown that up to 20% of the particles produced by a grinder are greater than 7.62 cm [1,2], making the feedstock they generate unsuitable for BCTs that require material to be reduced to less than one centimeter in length.

Chippers are an alternative to grinders and unlike grinders, they are sensitive to contamination which can dullen knives [3] and material size which influences handling and feeding capabilities [4]. The primary benefit of chipping is greater control of particle size which depends on a combination of factors related to machine configuration and mechanical properties of the wood [5], but ultimately improves the quality of the feedstock generated [6]. To facilitate the use of a chipper, forest residues should be separated. A recent study on separating and processing non-merchantable stem material from forest residues during a timber harvest operation demonstrated that additional handling increased operational costs by 10% [7]. The added value of the feedstock generated from the additional handling may justify the increased costs.

Specialized chippers, which can produce micro-chips that range between 6.4 and 9.5 mm in length [8], has been suggested as a means to prepare feedstock for in-woods BCTs. In addition to meeting BCT particle size requirements, micro-chips tend to have little variation in moisture content and a greater specific surface area improving drying efficiency in rotary or belt dryers [9]. Smaller feedstock particles can also improve torrefaction efficiency [10] and the durability of a densified product [11], which in combination can provide a high value bioproduct with consistent quality.

The current literature on the capabilities of a micro-chipper is limited to one known study. Thompson and Sprinkle [12] evaluated the fuel consumption and production rate of a modified disc-chipper producing conventional chips and micro-chips. The chipper produced an average of 31.5 bone dry metric tonnes (BDmT) of micro-chips per productive machine hour (PMH) while consuming 2.33 liters/BDmT of diesel. The chipper configuration used to make micro-chips decreased production by 12% and increased fuel consumption by 15%. On average, 74% of the chips produced were smaller than 12.7 mm in length. Producing small chips has proven to be more expensive as production drops and fuel consumption increases compared to producing larger sized wood chips (e.g., < 5 cm).

To improve our knowledge on the potential micro-chippers have in providing a quality feedstock, we conducted a field based experiment to evaluate the production rate, fuel consumption, and cost to produce 5.5 mm chips. Processed and unprocessed, softwood and hardwood stems that had aged 12 months in the field were chipped with a 12-knife, 570-kW drum micro-chipper. Particle size distribution, moisture content, bulk density, and ash content of the chips produced were analyzed. The goal of the study was to provide biomass feedstock production managers the ability to compare feedstock quality, production and cost of micro-chipping sorted forest residues with other applicable comminution machines.

2. Study Methods and Materials

2.1. Preparation of forest residues material for micro-chipping

The material chipped in this study were forest residues generated from three even-aged harvest units located on commercial timberlands owned by Green Diamond Resource Company in northern California. The harvested units were characterized as second-growth mixed conifer forest, comprised of softwood species (*Sequoia sempervirens, Pseudo-tsuga menzesii, Tsuga heterophylia, and Chrysolepis chrysophylla*) and a hardwood species (*Notholithcarpus densiflorus*).

Three sub-units, ranging between 2.43 - 3.64 hectares, were randomly selected from the three timber harvest units ranging between 7.69 – 8.50 hectares in area. In June of 2014 the logging contractor cut and separately piled: whole-trees greater than 20.3 cm diameter at breast height (DBH) for sawlog production and whole-trees less than 20.3 cm DBH for biomass, with a feller-buncher. Shortly after felling, a shovel with a standard log grapple forwarded the sawlog and biomass tree piles to the roadside. A dangle-head processor (John Deere 2454D with a Waratah 623 harvester head) processed (i.e., delimbed and bucked) and sorted sawlogs destined for a mill and hardwood stems (> 25.4 cm DBH) for an energy plant. In cooperation with our study, the processing operator separated out feedstock material including: small-diameter softwood and hardwood trees, and tree tops left from manufacturing sawlogs. Biomass trees and tree tops were further processed and piled separately into four different material types: processed softwood (PS), processed hardwood (PH), unprocessed softwood (US), unprocessed hardwood (UH). Stems greater than 20 m in length were cut into 7.6 to 9.1 m sections to facilitate transportation to a centralized chipping site.

Each material type (PS, PH, US, and UH) were characterized by volume and bark coverage. The length of each stem, small-end and large-end diameters were measured to estimate volume using the Smalian formula [13]. Stems that ended in a natural tip (i.e., unprocessed tops) were assumed to have a 2.54 cm small-end diameter. The amount of bark covering each sampled stem was visually estimated and recorded as a percentage. Species and the presence of foliage (needles or leaves) were also noted before micro-chipping the materials.

In August of 2014, two months after being cut, half of the biomass materials produced were removed and chipped for a separate study. The other half were left onsite for an additional 10-months to air dry in preparation for this and another study [14].

2.2. Micro-chipping of forest residues

The material prepared for this study was collected with a loader and placed into modified dump trucks for transport to the micro-chipping location. A Peterson Pacific 4300B drum chipper powered by a 570-kW engine comminuted each material type separately in an order determined by the contractor. This chipping started PS, then PH, UH, and finished with US. The chipper was equipped with a 12-knife and pocket drum configured to produce 6.35 mm chips and a grate system to prevent oversized and chip accelerator. Knives were not changed during the operation. Fifteen samples were collected from each material type using a collection tube method [15]. In total, two, 12-m chip trailers were filled with approximately 42 BDmT of micro-chips.

The process of collecting chip samples from the four different material types was done systematically to avoid bias. A collection tube made from 15.24 mm, 90 degree elbow attached to a 15.24 mm by 3.05 m PVC pipe was held in front of the chipper’s discharge spout to redirect chips down into a 19-liter collection bucket [15]. A bucket was filled with a sample approximately every two minutes. The chips collected in the bucket were poured into a plastic garbage bag and marked with a sample identification number. A 1.9-liter sub-sample was taken from each bag to evaluate moisture content. This bagged sub-sample was immediately weighed onsite with a portable balance, marked with its identification number in preparation for lab analysis.

2.3. Laboratory analyses: moisture content, particle size, bulk density, and ash content

A total of 60, 1.9-liter samples were collected from the micro-chipping operation to evaluate moisture content. The wet-basis moisture content of samples collected during the micro-chipping operation were determined using ASTM E871-82 standard test methods for green wood chips [16]. For this study, all samples were placed in paper bags and dried at 103°C for 48 hours.

During the field experiment, a total of 60 micro-chip samples were collected from the four different material types. These samples, were further separated into smaller sub-samples to conduct particle size, bulk density, and ash content analyses. The separation process involved inverting a 19-liter bucket over a large clean surface. The bucket was lifted vertically to allow the content to spill out forming a cone. A piece of sheet metal was used to systematically divide the pile into halves, quarters, and eighths for sub-sampling.

The method used to evaluate particle size distribution followed ANSI/ASAE S424.1 [17]. A subsample of approximately 2.5-liters was poured onto a stack of six, 30.5 cm diameter sieves and a bottom pan. The sieve stack and sample were shaken with a sieve shaker for two minutes. The shaking motion fractioned the samples into seven particle size classes: < 3.18, 3.18 – 6.35, 6.35 - 9.53, 9.53 - 12.70, 12.70 - 19.05, 19.05 - 25.40, and >25.40 mm. The oven-dried mass of micro-chips captured on each sieve was used to calculate the geometric mean particle length (GMPL) along with standard deviations for each sample.

The bulk density for each micro-chip sample was determined using a modified version of ISO 15103 tap test [18]. A plastic bucket with a volume of 8.8-liter, a height-to-diameter ratio of 1.26, and a taper of 9.7 cm/m was used instead of the suggested 50- or 10-liter container. A smaller container was used to reduce the amount of sample collected.

The method used to determine ash content was consistent with protocols established by the National Renewable Energy Lab [19]. A 1.9-liter sub-sample was further processed using a 16.4 cm^3 laboratory Wiley mill running at 800 rpm with a 2-mm screen. Approximately 6.5 g of finely milled material was randomly scooped into a ceramic crucible and oven dried for 48 hours at 103°C. The referenced method was modified by pre-igniting the sample prior to ashing in a muffle furnace. Desiccant chambers were used to control moisture absorption after oven drying and ashing in the muffle furnace. The standard muffle furnace procedure without a ramping program was followed [19]. Three samples were prepared and analyzed for each micro-chip sample.

2.4. Evaluating machine productivity, fuel consumption, and cost

Time and motion study data were collected to estimate micro-chipping productivity using a standard work study technique [20]. The time required to fill a 69 m^3 chip van minus delays was observed to determine productive machine time. The type of material fed into the micro-chipper was recorded for each cycle. Moisture content of samples collected during the experiment were used to determine BDmT from recorded scale weights. Hourly cost to operate the chipper was calculated using the machine rate calculation method [21,22] with input values and assumptions listed in Table 1. Diesel fuel consumed during the chipping operation was estimated by starting the operation with a full tank and then measuring the amount needed to refill the tank after each trailer was filled. The fuel truck was equipped with a metered pump allowing us to measure the amount of diesel fuel consumed to a tenth of a gallon.

2.5. Statistical Analysis

The data collected from the different analyses were statistically tested using R Statistics [23]. One-way ANOVA was performed to determine if there were significant differences in means between the four main material types (i.e., PS, PH, US, and UH) for each analyses. A two-way ANOVA was also used to test determine if species (softwood or hardwood) and treatment (processed or unprocessed) and their interactions were statistically significant. Normality assumption were visually examining Q-Q plots and verifying using the Shapiro-Wilks test. The equal variance assumption was checked by examining residual v. fitted plots and tested using the Breush-Pagan test. Post-hoc analyses using the Tukey HSD multiple comparison test were conducted to examine possible relationships between variables. Statistical significance was based on a p-value that was set at a 0.05 level.

3. Results and Discussion

3.1. Characteristics of forest residues used for the study

A characterization of the forest residue material used in the study prior to micro-chipping provided information about the size and volume of material fed into the micro-chipper (Table 2).

The residues' characteristics were mostly determined by the processing machine's capabilities and the operator. We noticed that almost all of the unprocessed stems were tree tops which were left from the sawlog processing. This was mainly due to a stem's propensity to break when processing below 5.0 – 7.6 cm in diameter, which generally caused operational delays. Processed stems were, therefore, the portion of the stem before the top (Figure 1). For this reason, we thought there would be a difference in diameter and volume between processed and unprocessed stems, which has been shown to have an effect on productivity and particle size distribution. Results from statistical tests showed that the mean volume of sampled stems were not found to be statistically different between processed and unprocessed stems. However, the average diameter for processed stems was significantly greater. The processors knives and three feed-rollers also created enough force to loosen and sheer bark. On average, we found that processing stems resulted a 26% reduction in bark cover in both hardwood and softwood stems.

The average moisture content of the sampled micro-chips ranged between 18 and 23% (Table 3). Results from the statistical analysis indicated a significant interaction between variables indicating that the effect treatment had on moisture content was different for hardwood and softwood. Post hoc multiple comparison test indicated that PH's mean moisture content was significantly greater than those of UH, PS, and US.

Understanding moisture content of the material chipped was important because it has been shown to have an impact on particle size distribution, and machine productivity and fuel consumption [24,25]. The material's unusually low moisture content generated enough heat from friction to cause the micro-chipper to smoke during operation. To prevent an ignition, a fire hose was used to continuously spray water directly onto the material entering the chipper's in-feed. We anticipated an increase in the moisture content of the samples collected. However, when compared to chips generated in a concurrent study using the same materials at the same time [14], we found no significant difference between the corresponding material types.

3.2. Particle size distribution of micro-chips

The GMPL of sampled micro-chips from the four material types chipped in this study ranged between 4.3 and 6.5 mm (Table 3). The results showed that PS was significantly greater in GMPL compared to US chips, whereas PH and UH were statistically the same. We hypothesized that processing (i.e., delimbing) either softwood or hardwood stems would reduce the GMPL of chips. This was based on research by Spinelli et al. [26] where they found that flexible branch material could sometimes get “pulled” through a chipper without being cut. These expected that these oversized branch sections would increase the GMPL of this studies samples. However, the results were contrary to their findings. The influencing factor affecting our results was the difference in stem diameter between PS and US. As stated earlier there was a significant difference in the average diameter between the two material types (processed vs. unprocessed) due to processing methods. Analysis indicated that diameter was a significant factor affecting the GMPL for both hardwood and softwood chips. In addition there was a moderately and weaker positive correlation with GMPL for softwood for hardwood, respectively, suggesting that diameter had a greater influence on softwood material leading to chips with shorter GMPLs.

In addition to stem diameter, bark and foliage content may have also influenced the GMPL of the different materials. It has been shown in past studies that bark and foliage contribute to greater proportions of fine fractions [27,28]. Softwood bark often lack the fibrous structure, which gives it strength, leading to a greater tendency to fracture under compressive forces, such as those generated from knife impact [29]. Results from this study showed that the proportion of US particles < 3.18 mm was 20% greater than PS (Figure 2). This corresponds with observations which showed 26% more bark cover on US compared to PS. Conversely, this phenomena was not observed when comparing PH and UH. This may be because tanoak, the hardwood species used in this study, has bark that contains schlerids, or fibrous bundles that increase its strength [30]. Even though PH and UH are not statistically different, there is a greater proportion of fines in the UH samples. This difference might be due to fines generated from pulverizing foliage, which was still present at the time of the study.

Another factor that may have contributed to the difference in GMPL between US and PS is knife wear. During the study we chipped 42 tonnes of material in which US was last to go through the chipper. For this reason, the results may have been influenced to some degree, by knife wear. Nati et al. [3] found that knife wear resulted in a noticeable difference in particle size distribution after 80 tonnes of fresh poplar were chipped. Groover [31] found an increase in the amount of particles < 10 mm when after knives were changed at 100 tonnes, or five chip can loads. Unfortunately, the study did not include a method to measure the effect of blade wear on particle size, so we were not able to conclusively state that this was a major factor. Future studies should carefully consider the effects of knife wear when evaluating micro-chippers.

Material types with greater proportions of smaller sized particles (i.e., US and UH) had more linear curves compared to the other material types (Fig. 2). This was due in part to an inadequate number of smaller sieves needed to provide better distribution resolution. We suggest that future studies use a wider range of sieves to further separate the fine fractions when evaluating micro-chip distributions.

3.3. Bulk density and ash content of micro-chips

The bulk density of the four material types ranged from 226.8 – 299.5 kg/m^3 (Table 3). There was no significant interaction between species and treatment on bulk density. In this study, species was the only significant factor influencing bulk density.

We initially hypothesized that processed stems would generate a more homogenous particles-size over unprocessed stems resulting in a significantly different bulk density. This was based on results comparing bulk densities of highly variable particles found in hogfuel to more homogenous samples found in wood chips [14]. We found that there was no significant difference between the bulk densities of PH and UH, which was also true for PS. Therefore, there was no evidence to support that processing hardwood or softwood in this study had a significant influence on micro-chip bulk density.

The average bulk density of softwood and hardwood material was 231.5 and 296.2 kg/m^3, respectively. The difference between species can be explained by their specific gravities. The specific gravity of the softwoods; redwood (0.36), Douglas-fir (0.45), and western hemlock (0.42) is considerably greater than the hardwood; tanoak (0.58) [32].

The bulk density of the same four material types were evaluated in a concurrent study using a disc chipper configured to cut 19.05 mm chips [14]. The bulk densities for PS, PH, US, and UH, were 203.2, 251.5, 217.1, and 251.5 kg/m^3, respectively. There was no significant difference in the moisture content of the material used in the two studies. However, because of the difference in mean geometric particle size, the average bulk density of micro-chipped material was 13% greater than that of the larger chip.

Ash content for the four different material types ranged from 0.25 and 1.18% of the oven-dry sample weight (Table 3). Two-way ANOVA indicated that the two main factor, species and treatment, were significant as well as their interaction on ash content. The mean ash content of PS and US were the only two material types not found to be significantly different by way of multiple comparison analysis.

Past studies [33,34,28] have shown that higher bark content in samples contributed to an increase in ash content. Therefore, a reduction in bark from processing would be a contributing factor resulting in a difference in the ash content between processed and unprocessed stems. Our study results showed similar outcomes, but only between PH and UH. One possible reason could be that UH still had foliage attached at the time of the study. Lehtikangas [33], and Pettersson and Nordfjell [35], both observed a reduction in ash content with a reduction in foliage.

3.4. Chipping productivity, fuel consumption and cost

The micro-chipper was observed producing an average of 17 BDmT of chips every 48 minutes with an average delay time of 20 minutes (Table 4). The hourly machine rate used to determine cost per tonne was $378.42/PMH (Table 1).

The productivity of the 4300 B drum chipper, 37 BDmT/PMH, was slightly lower than the modified disc chipper, 38 BDmT/PMH, used in Thompson and Sprinkle's [12] study. To make this comparison we adjusted their original production value by assuming a 45% moisture content. The observed delay during the experiment was primarily operational and related to loader activities.

The average fuel consumption of the 12-knife, 570-kW micro-chipper that was used for this study was greater than that of the 8-knife, 522-kW disc chipper reported by Thompson and Sprinkle [12]. We converted their 0.96 liters/tonne value by the reported moisture content (50%) and derived a fuel consumption of 1.92 liters/BDmT. The difference in fuel consumption could be, in part, due to differences chipper type (disc vs drum), engine power, knife configuration, material type, and moisture content. Making a direct comparison on equipment productivity rates can be difficult for these reasons [4].

Even though the production data for this study is limited compared to other studies [36,3,37] the productivity and fuel consumption estimates that we provide are still useful as a baseline to compare with future studies.

It should be noted that operational cost to produce, transport, or load material into the chipper was not considered. In addition, move in/out, profit and loss, and other supporting equipment were not considered.

Based on the results from this study, the micro-chipper's productivity and fuel consumption are comparable to results found for high production chippers and grinders with engines greater than 298-kW found in the literature (Table 5). The two primary differences between the micro-chipper and other comminution machines are operational costs and the particle size range it produces. The results from this and other studies show that on average the micro-chipper costs 35 and 30% less to operate on a dollar per dry ton basis, compared to chippers and grinders, respectively. Micro-chips from this study had a bulk density 13% greater than standard 19.06 mm chips produced in a concurrent study using the same material [14].

4. Conclusion

We conducted a study to evaluate the feedstock quality, production rate, fuel consumption, and cost to produce 3.18 mm micro-chips. Processed and unprocessed, softwood and hardwood stems generated from forest residues were allowed to age 12 months in field and then chipped with a 12 knife, 570-kW drum chipper. The moisture content of the four material types averaged 20%, which might have had an effect on the size distribution of chips produced. Processing, i.e., delimbing, stem wood did not have a significant effect on the bulk density of the two different material types (hardwood and softwood) comminuted in this study. However, microchipping increased bulk density by 13% compared to larger chips made with the same forest residues in a concurrent study. This difference can be the answer to improving transportation efficiency in situations where trailers are volume-limited from loading material low in moisture content. Managers can capitalize on these benefits of micro-chipping and reduce the overall cost of biomass recovery operations.

On average the chipper produced 33.93 BDmT/PMH at a cost of $11.16/BDmT, which is comparable to results found for larger model, high production, chippers and grinders found in the literature. Aside from cost, managers should also consider meeting the feedstock size specifications required by the consumer. The micro-chipper was capable of producing chips with a geometric mean size between 4.3 and 6.5 mm, which is desirable for such conversion technologies as torrefaction, pelletizing, and briquetting.

This micro-chipping study was a field experiment which may not truly represent the productivity and cost of an actual production operation. In addition, it should be mentioned that costs reported in this study do not cover overhead, profit and loss, and other operational expenses such as support equipment, loading, and move in/out costs. The cost results of this study may also vary based on a number of different factors, such as species, moisture content, knife wear, and operator experience.

This study provides some practical information for feedstock procurement managers when considering the use of a micro-chipper to comminute forest residues, especially in regards to meeting specific feedstock requirements for various BCTs.

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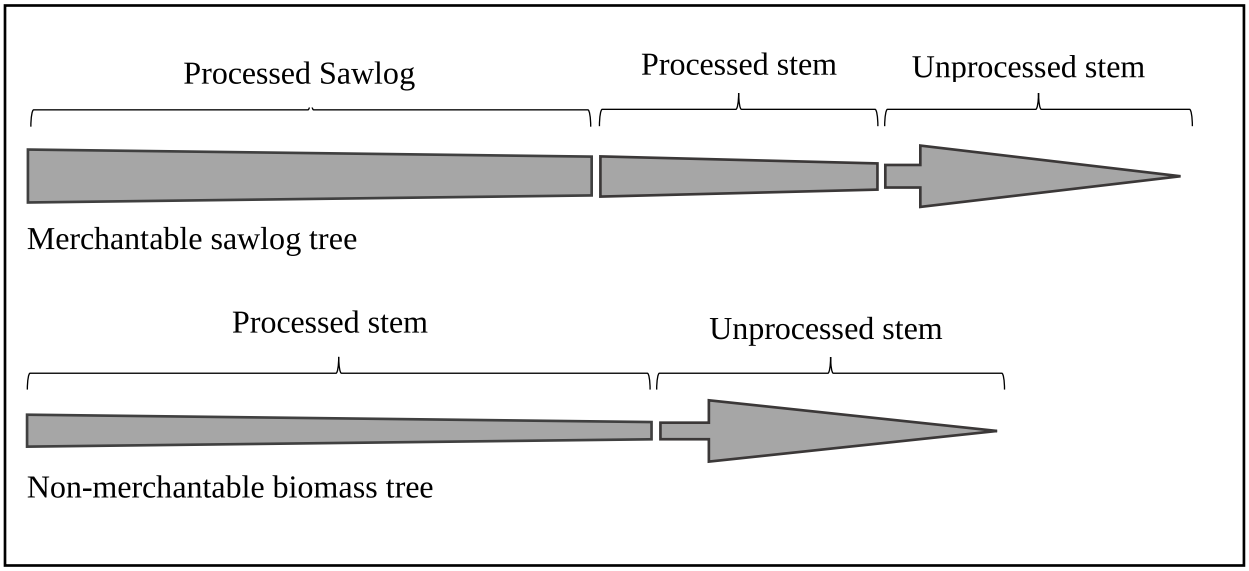

Figure 1. Sections of merchantable sawlog and non-merchantable trees used to produce processed and unprocessed stems in this study.

Figure 2. Cumulative distribution of % micro-chip mass passing through screening sieves for processed softwood (PS), unprocessed softwood (US), processed hardwood (PH), and unprocessed hardwood (UH).

Table 1. Input values and assumptions used to estimate an hourly cost of a 12-knife and pocket, 570-kW drum micro-chipper.

Purchase price ($)	514,000	Utilization (%)	80
Salvage value (%)	20	Repair and maintenance (% of annual depreciation)	100
Life (years)	5	Fuel cost ($/liter)	1.02
Interest (%)	10	Fuel use (liter/PMH)	75.6
Insurance (%)	3	Lube cost (% of fuel cost)	36.8
Taxes (%)	2	Wages and benefits ($/SMH)	0
Total machine costs			
Hourly machine cost ($/Scheduled Machine Hour)			302.74
Hourly machine cost ($/Productive Machine Hour)			378.42

Table 2. Average volume, stem diameter and bark cover of processed softwood (PS), processed hardwood (PH), unprocessed softwood (US), and unprocessed hardwood (UH) chipped in the study.

	PS	PH	US	UH
Stem volume (m^3/piece)	0.19 ±0.07	0.17 ±0.07	0.19 ±0.09	0.15 ±0.06
Stem diameter (cm)	17.0 ±2.3	18.0 ±2.8	15.5 ±1.8	14.7±2.0
Bark cover (% of total stem area)	65 ±27	71 ±28	92 ±13	96 ±6

Table 3. Moisture content, geometric mean particle length (GMPL), bulk density and ash content of processed softwood (PS), processed hardwood (PH), unprocessed softwood (US) and unprocessed hardwood (UH) samples.

	Material type			
	PS	PH	US	UH
Moisture content (%)[†]	18 ±3	23 ±4	20 ±4	20 ±8
GMPL (mm)	5.8 ±2.1	5.4 ±2.1	4.3 ±2.2	6.5 ±2.3
Bulk density (kg/m^3)	236.3 ±20.1	299.5 ±25.0	226.8 ±16.0	292.9 ±41.8
Ash content (%)[*]	0.25 ±0.09	0.88 ±0.24	0.35 ±0.32	1.18 ±0.18

[†] Moisture content evaluated on percent wet basis and reported.

[*] The weight of the ash divided by the original oven-dried sample weight multiplied by 100.

Table 4. Productivity, fuel consumption, and cost to micro-chip and fill three trailers with a mix of softwood and hardwood stem wood chips. Cost to load micro-chipper not included.

Trailer load	Productivity BDmT*/PMH	Fuel consumption		Cost $/BDmT*	Softwood / Hardwood % mix
		liter/ BDmT*	liter/PMH		
1	33.49	2.77	92.84	11.26	50 / 50
2	39.67	2.55	101.05	9.50	32 / 70
Average	36.58	2.66	96.95	10.38	

[*] Green tonne values were converted to bone dry metric tonnes by multiplying by the average moisture content (20%).
PMH: productive machine hour.

Table 5. Comparison of comminution machine production, fuel consumption, feedstock bulk density and particle size. Values are reported ranges for machines greater than 300-kW in the literature since 2010. Standard units were converted to SI and adjustments for moisture content using published data were performed for comparability.

	Sawdust	Micro-chipper	Chipper	Grinder
Production (BDmT/PMH)	18 - 28[38]	32 [12] - 37[a]	7[37] - 32[14]	22[41] - 50[1]
Fuel Consumption (liter/BDmT)	0.96 - 1.50[38]	2.33[12] - 2.66[a]	1.10[3] - 3.80[39]	2.2[2] - 7.2[1]
Dry Bulk Density (kg/m^3)	235 - 281[38]	189 - 240[a]	162 - 201[14]	137[14] - 167[2]
Particle Size (mm)	4 - 7[38]	4[a] - 13[12]	2 - 12[14]	9.5 - 76.1[2]
Cost ($/BDmT)[†]	3.10 - 4.83[38]	9.50 - 11.26[a]	11.87[7] - 19.90[40]	11.78[1] -17.82[41]

[a] Present study
[†] Does not include cost to load comminution machine.