EVALUATING THE PRODUCTION COST AND QUALITY OF FEEDSTOCK PRODUCED BY A SAWDUST MACHINE

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Evaluating the production cost and quality of feedstock produced by a sawdust machine

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Abstract

The utilization of forest residues as a woody biomass feedstock for the production of bioenergy and bioproducts requires processing (i.e., comminution) to meet feedstock specifications, such as moisture content and particle size. The objective of this study was to determine the effect of small diameter processed hardwood (SH) and small and large diameter processed softwood (SS and LS) stems had on the productivity and cost of a track mounted sawdust machine that produced sawdust. In addition, moisture content, particle size distribution, bulk density, and the effect of knife wear were evaluated. The sawdust machine's 298-kW engine was capable of comminuting all metarial types except the LH stems. The machine's productivity ranged between 18.3 and 26.7 bone-dry metric ton (BDmT)/productive machine hour (PMH) at a cost of US $5.3 and US $3.6/BDmT, respectively. The moisture content of material used in the study ranged between 26 to 36%. The geometric mean particle lengths for SH, SS, and LS were 4.7, 5.3, and 4.4 mm, respectively. The machine could not process LH materials due to limited power. The bulk density of feedstock produced ranged between 234 to 281 kg/m^3. Analysis indicated that knife wear did not have a significant effect on comminution productivity and feedstock quality while comminuting 60 green metric tons (GmT) of forest residues. The results from this study suggest that this sawdust machine can be useful in producing feedstock for new biomass conversion technologies that require small, uniform particles.

***Keyword*:** woody biomass, bioenergy, micro-chipper, comminution

Introduction

Forest residues in the form of tree tops, limbs, and non-merchantable trees are a potential source of feedstock for producing bioenergy (e.g., heat and electricity) and bioproducts including liquid fuels, biochar, torrefied wood, pellets, briquettes, and nanocellulosic fibers [1,2,3,4].

Grinding, which produces hogfuel by hammering material into smaller peices has been shown to be highly effective at comminuting material heterogenous in size that may be contaminated with soil and rock [5, 6]. For this reason, they are typically used when forest residues are indescriminantly piled. Conversely, the knives used in drum or disc chippers are sensitive to rock contamination [7, 8] and are more efficient comminuting material homogenous in size, such as stem wood rather than branches [9, 10] and would therefore require the separation of residues [11]. The primary advantage of chipping stem wood compared to grinding unsorted residues is a higher quality feedstock with a more uniform particle size distribution [12]. Processing (i.e., delimbing stems) sorted forest residue stems prior to chipping has been shown to further improve the quality of feedstock produced by reducing ash content and reducing the amount of over- and under-sized particles [12].

In addition to producing uniform feedstock, chippers can also be configured to produce different size wood chips. Small chips have a greater bulk density compared to larger chips [13] which has a direct effect on feedstock storage, transportation costs [14], and biomass conversion processes [15]. For example, producing small chips can increase a feedstock's shipping density resulting in an increase of transportation efficiency and a reduction in cost [16].

The ability to produce smaller sized particles (< 4.0 mm in length) is also important to consider when providing a feedstock for biomass conversion technologies. Feedstock size has been shown to influence extrusion and pyrolysis processes by having an effect on binding, drying, and reaction time [17, 18, 19]. A feedstock's geometric mean length, width, and thickness, as well as uniformity directly affects conversion efficiency, product quality, and durability. Densification technology was found to be more effective in producing a higher quality (i.e., durable and dense) product [20] when using small sized feedstock, compared to briquettes and pellets produced from larger chips [21, 22]. A different study had agreed that blending a 10-20% feedstock of fine particles (< 4.76 mm) would improve densification quality due to interparticle bonding [19].

Biomass gasification, a technology often used to produce gas and generate electrical energy, can be sensitive to particle size [23, 24]. When feedstock particles ranging from 0.13 to 0.30 mm in size were pyrolyzed at a temperature between 500-900 ℃, there was a greater production output and quality of biogas [23, 25]. In addition, the conversion of biomass with larger (> 2.0 mm) particle size resulted in a slower gas diffusion speed and lower quality gas [23, 26].

Torrefaction is a thermochemical process using temperatures ranging between 200 to 300 ℃ [26, 27] to convert organic biomass into a charcoal-like material, which has better fuel characteristics than the original biomass. There are a number of studies that have examined the effect of reaction temperature and reactor residence time on the torrefaction process [27, 29, 30], but only a few studies have been performed on the effect particle size has on torrefaction. Basu et al. [30] evaluated the effect of seven different feedstock sizes on a torrefaction process, observing that energy and mass yield produced more when the smaller size (4.76 mm in diameter) torrefied at 250 ℃. However, Peng et al. [31] investigated the effect of three particles sizes (0.23, 0.67, and 0.81 mm), finding that as the size of a particle decreased, the weight loss rate increased, but the energy yield decreased during the torrefaction process.

The ability to control particle size when chipping can be challenging. Aside form machine type and configuration, there are a number of factors such as moisture content, wood hardness and strength, and annual growth ring characteristics [32, 33]. Suadicani and Gamborg [34] investigated the effect of different moisture content (60 vs. 40%). They found that freshly felled whole trees with a 60% moisture content produced a greater proportion of fine chips and less over-sized chips compared to whole trees with a lower moisture content. In a study by Watson and Stevenson [35], logs with low moisture content increased the over-sized chip and decreased the amount of fine particles. Particularly, woody biomass with either low and high moisture content produced chips with a greater proportion of over-sized and fine particle sizes [32, 36, 37] because moisture content influences wood strength [32].

Current research on a producing small sized wood chips or microchips (< 10 mm) is very limited. Past studies have reported micro-chipper's productivity and feedstock quality when producing 6 – 10 mm chips in diameter [12, 38]. However, producing chips smaller than 4 mm using a sawdust machine is largely unknown.

In this study, we evaluated the productivity and cost of a 294-kW (400-hp) track mounted sawdust machine to determine its capabilities when comminuting forest residues to produce sawdust sized (2 to 4 mm) chips as feedstock for biomass conversion. The primary objective was to determine the effect material type and diameter had on the performance of the sawdust machine. In addition, we evaluated the quality of feedstock produced during the tests. More specifically, we analyzed moisture content, particle size distribution, and bulk density of feedstocks produced from four different marterial types: small (< 15 cm) and large (15 – 30 cm) diameter processed hardwood (LH and SH, respectively) and softwood (SS and LS, respectively). As a precaution, we took steps to evaluate the potential confounding influence of knife wear. During the operation, knives were not changed. Therefore, prior to changing to a new material, we tested for possible knife wear by comminuting a control material, i.e., 0.1 m × 0.1 m × 2.4 m Douglas-fir boards, and evaluated any change in particle size and or production rate. Conclusions from this study will be valuable to managers who face the challenges of meeting smaller sized woody biomass feedstock specifications required by different conversion technologies. Information from this study will also allow managers to compare the performance and cost of this machine with other options when comminuting forest residues.

Methods and Materials

Description of material types and sawdust machine used in the experiment

The study site was located in Humboldt County, northern California in a harvested unit on Green Diamond Resource Company timberland. The harvested stand was second growth mixed-conifer stand composed of redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menzesii*), western hemlock (*Tsuga heterophylla*), and tanoak (*Notholithcarpus densiflorus*). The unit was clear-cut using a feller-buncher. Whole trees were shovel logged to roadside or landings. A dangle-head processor (John Deere 2454D with a Waratah 623 processing head) delimbed, bucked, sorted and piled approximately 80 green metric tons (GmT) of four different material types: small-diameter softwood stems (SS; < 20 cm); large-diameter softwood stems (LS; 20 – 30 cm); small-diameter hardwood stems (SH; < 20 cm); and large-diameter hardwood stems (LH; 20 – 30 cm). Slash piles were commonly composed of processed and sorted stems in the 15 – 30 cm diameter range in preparation for transportation to a biomass conversion technology [12, 39] particularly in Northern California. Stem wood used for this study were processed to a 6 to 7 m length to facilitate handling and to control the influence of stem length on comminution productivity [12].

The track-based sawdust machine used in this study was a prototype model manufactured with a 294-kW Doosan diesel engine which powered a 1.2 m (height) by 0.8 m (diameter) concave drum equipped with an array of 582 tungsten alloy knives desinged to produce sawdust size (2 to 4 mm) (Figure 1). At the beginning of the experiment new knives were installed. The machine was equiped with four free-spinning rollers that positioned stem wood material onto a metal-toothed in-feed conveyor belt that pulled the material toward the chipping drum. The machine was designed with an additional metal toothed conveyor above and at an angle to provide a downward pressure on material entering the 0.4 m by 0.7 m in-feed mouth. The conveyor was controlled by the operator who could select between the belt moving towards or away from the chipping drum. Wood sawdust exiting the chipping chamber was blown onto a 2.5 m by 0.7 m rubber conveyor belt. The sawdust machine was positioned on a large landing with a tracked loader using standard log grapples and a roll-off bin truck equipped with a 15 m^3 bin (Figure 1).

Field data collection

Prior to chipping, the four material types were characterized by stem size (Table 1). Average stem volume was calculated using the Smalian's formula for each material type [40]. Standard time and motion study methods were used to evaluate machine productivity [41]. A production cycle was defined as the time necessary to chip a single stem. Because the machine's engine had difficulty maintaining drum speed when chipping a large number of stems at a time. The cycle started when the processed stem made contact with the chipping drum, which was audibly discernable, and ended when the chipping sound stopped. All other times were recorded as delays in the operation. During the experiment, three 15 m^3 bins were filled with sawdust from a single material type for each material type (i.e., SS, LS, SH, and LH). The total amount of time to fill a bin (beginning with the first cycle to the end of the last cycle) was recorded. To determine the machine rate, pure chipping and delay times sum up to gross-cycle times and refer to scheduled machine hours (SMH). Thus, machine rate was pure chipping times per day divided by the scheduled machine hours per day.

Loaded bin weights were measured by driving the roll-off bin truck onto a PT300™ RFX portable wheel-load scale installed on-site. The scale, which is capable of weighing up to 20 tonnes, is accurate to within ± 1% of the reading. Standard methods were used to calculate hourly machine cost for the sawdust machine and assumptions are listed in Table 2 [42].

Sawdust samples were collected during the operation for lab analysis of feedstock quality. An 8.8-liter bucket was held under the sawdust machine's discharge conveyor belt to collect samples. A single sample, equaling approximately two bucket loads, was collected every three or four minutes until 10 samples were collected for each material type of SH, LH, SS, and LS. Every sample was placed in plastic trash bags and marked with a sample number. A 3.8-liter subsample was taken from each sample to assess moisture content. Each subsample was immediately weighed in the field with a portable scale to record green weight.

The fuel consumed during each material type test was measured by recording the amount of fuel needed to refill the tank to a pre-marked level on a fuel sight gauge. A 1,000 ml graduated cylinder was used to measure [43, 44]. From this data, we calculated liters of fuel consumed per hour and applied this to the cost formula.

For this study we chose to test the effect of knife wear by comminuting a control material, 0.1 m × 0.1 m × 2.4 m Douglas-fir boards. Control materials were chipped before and after each new material type. Sawdust samples were collected the same way SH, LH, SS, and LS test samples were collected. Particle size of chips created from these boards to see if there was any change over time, possibly indicating knife wear.

Lab work and data analysis

In total, 110 samples (Table 3) were put into paper bags and oven-dried at 105°C for 48 hours. The moisture content of each sawdust sample was determined by following the ASTM D4442-07 method [45].

The particle size distribution of sawdust samples produced during the experiment was determined by ASTM E11-16 standard [46]. A 2.5-liter subsample was removed from each sample and separated into seven size-classes (< 0.84 mm, 0.84 – 1.00 mm, 1.00 – 1.41 mm, 1.41 – 2.00 mm, 2.00 – 2.80 mm, 2.80 – 4.00 mm, and > 4.00 mm) using a mechanical sieve shaker including six sieves and a bottom pan (Table 4). After screening, the material captured in each sieve was weighed. The mass of each sieve was used to determine the percentage of total mass to get a size distribution of sawdust. We also calculated the geometric mean particle size using equations which adopted from a method used to express particle size of chopped forage material by screening [47].

The bulk density of each sample was determined using a modified version of ISO 15103 [48]. In our analysis, we used an 8.8-liter bucket to conduct two tap tests for each sample. The test was repeated if the two bulk density results differed by more than 5%.

The study data was analyzed using SPSS Statistics software [49]. Statistical methods included homogeneity of variance tests (Levene's test). Analysis of Variance (ANOVA) was used for checking the equality of means, obtained at the different treatments. Post-hoc tests were carried out according to the Scheffe's test (parametric) or the Dunnett's T3 test (non-parametric). For example, when the Levene's P-value was smaller than 0.05, the Dunnett's T3 test was used. Pearson's correlation tests were used to determine the relationship between moisture content, geometric mean particle size, and bulk density. A 5% alpha level was the significance criteria used for statistical tests.

Results and Discussion

Productivity and cost of converting stem wood into sawdust size chips

The study was designed to test the sawdust machine while comminuting four different material types. However, the machine's 298-kW motor had difficulty maintaining drum speed when chipping the LH, leading to prolonged delays and occasional machine malfunction. For this reason, we excluded LH from the study and focused on the three other material types.

On average, the machine was capable of producing 18.3 to 26.7 BDmT of sawdust/PMH at a cost of US \$5.3 and US \$3.6/BDmT, respectively (Table 1). Despite having longer average delay free cycle time, the production rate for LS was significantly greater (25%) compared to the SS and SH ($P < 0.05$) by one-way ANOVA and Scheffe's test. Greater production when comminuting LS was mainly due to larger stem volume, which was two times greater than SS and SH.

During the comminution process, average fuel consumption varied between 26-29 liter/ SMH. There was no significant effect of material types ($P > 0.05$) by one-way ANOVA and Scheffe's test. Nati et al. [44] found that material type had no effect on fuel consumption but rather it was the mechanism of comminution (i.e., drum vs. disc) had a greater influence. Thus, LS configuration produced a much larger quanty of sawdust while the same amount of fuel consumption.We found that diameter size had a considerable impact on chipping time ($P < 0.001$). Stem diameter size and comminuting time were directly related ($R^2 > 0.40$). Thus, stem diameter size was a significant variable in this study.

We noticed that the productivity of the prototype sawdust machine was influenced by material conveyance and motor size. The in-feed conveyor belt, which used metal teeth to pull the material into the drum, would often fail to maintain a grip on the stem. This required the loader to assist feeding the sawdust machine reducing productivity. The percentage of delays from infeed issues in this case study was 50%. When the material began chipping, especially for larger stems, the resistance on the chipper's drum would overpower the motor. The drum's rotation speed without a load was 2,000 revolutions per minute (RPM). When chipping, it would drop as the motor was put under stress to maintain drum RPMs. When the drum RPMs would drop below 1500 the operator would reverse the in-feed belt and allowed the RPMs to regain speed. The time required to regain optimal drum speed accounted for 7, 8, and 13% of total work cycle time for the SS, SH, LS tests, respectively. One technique used to alleviate this, was to back the material out of the chipper before the drum's RPM dropped below a critical point. This method reduced the time needed to bring the drum up to speed. For this reason, we feel that the sawdust machine could improve its productivity by using a larger motor. Further, size recustion equipment (i.e., chipper and grinder) engine power was commonly used to between 570-kW and 782-kW machines [5, 12, 50, 51], particularly in Northern California.

Compared to other chippers, the sawdust machine's chipping productivity was lower. For example, a Peterson Pacific 4300B, 570-kW micro-chipper was reported chipping processed softwood and hardwood stems, averaging 0.18 m^3 in log volume with 20% moisture content, at a rate of 33.9 BDmT/PMH and an estimated cost of US $11.2/BDmT [12]. We can attribute the difference in productivity to engine power which was also observed in Spinelli and Hartsough study [52]. The authors found a chipping productivity was inversly associated to engine power.

Quality of Sawdust Produced During the Study

Moisture content of sawdust

The average moisture content of the sawdust sampled from the three material types chipped in this study ranged between 26 and 36% (Table 1). The materials prepared for this study were residues left from a logging operation that occurred in June of 2016, one month prior to chipping. LS was the only material type that was significantly different in mean moisture content (36%) compared to SS (26%) and SH (29%) by Dunnett's T3 post-hoc test (LS vs. SS and SH, $P < 0.001$). Several studies have reported that moisture content had an inverse relationship on the size of the particle produced [32, 33, 35, 37]. In our study, however, the moisture content had a weak to moderate negative correlation and no pattern with geometric mean particle length (Figure 3). When stem moisture content was fresh, the chips were less homogeneous compared to particles with 18-25% moisture content [35, 36].

Particle size distibution of sawdust

The geometric mean particle length of sawdust sampled from the three material types (SH, SS, and LS) were 4.7 ± 0.1, 5.3 ± 0.1, and 4.4 ± 0.1 mm, respectively (Figure 4). There was a significant difference between geometric means of the different treatments ($F(3,16)=31.6274$, $P < 0.001$) by one-way ANOVA and Scheffe's test. The data analysis results of the sawdust size distribution are shown in Figure 5 and 6. The size class with the greatest proportion, ranging between 74 and 84%, were between 0.84 and 4.00 mm, depending on material type. The LS test produced the greatest proportion of acceptable particle size (84%) compared to SS and SH. Over-sized particles (greater than 4.00 mm) were significantly more frequent in the SS tests ($P < 0.001$). The percentage of fine particles (less than 0.84 mm) was higher in SH test than in other tests ($P < 0.05$).

There are two main factors that influenced particle size: physical characteristics of the material (e.g., shape, density, and moisture content) [5, 12, 35, 37, 47, 51] and machine characteristics (e.g., chipper type, knife sharpness and angle, and rotation speed) [49, 52, 53]. In this study, the goal was to control for as many of these factors as possible to reduce the effect of confounding variables. One interesting phenomenon we observed was the relationship between the material and the machine. The density of the SH and the larger volume of the LS created stress on the 294-kW motor. The resistance exerted by the material reduced drum speed and may have had an effect on the particle size. Two studies, Hoque et al. [52] and Hernandez and Jacques [53] both found that chipper engine power influenced chip piece size. More specifically, higher chipper rotating speeds produced a greater percentage of small size chips. Results from this study are similar findings. The ratio of particles less than 0.84 mm in size increased with the SH and LS tests. Both of these material types chipped at a faster rate indicating that drum rotation speed was not reduced during the operation.

Watson and Stevenson [35] and Van der Merwe et al. [51] found that over-sized chip production declined 3-10% with an increase in stem diameter and moisture content. Other study confirmed previous finding about the primary effect of stem diameter size on moisture content [54]. Therefore, interactions between respective stem's diameter and moisture content had an effect on feedstock size distribution during chipping process. Similar results were found in our study. The LS test produced 12% fewer particles greater than 4.00 mm compared to SS.

Bulk density of sawdust

The packing density of the chips produced in this study ranged between 233 and 281 kg/m^3 on a wet basis. The moisture content of chips did not have an inflence on bulk density when conducting a tap tests [55]. Dunnett's T3 post-hoc test indicated that SS was the only material type that was significantly different with the lowest value in mean bulk density compared to other material types ($P < 0.001$). The bulk density of small size chips increased 20% in comparison with the larger sized chips [12].

The mean bulk density of the sawdust evaluated showed a similar pattern of those reported for a micro-chipping study where hardwood chips had a greater bulk density compared to softwood [10]. The difference between species was attributed to the difference in the specific gravity between hardwood (tanoak, 0.58) and softwood (Douglas-fir, 0.45) [56].

Knife wear during communition tests

Knife wear has shown to be a factor contributing to particle size distribution [57, 58], therefore a new set of knifes should have been installed after each material type test. However, due to high cost to replace a set of knives, the effect of knife wear on sawdust quality and sawdust machine productivity was evaluated by monitoring changes in a uniform or "control" material type.

The geometric mean length of particles produced from the chipped Douglas-fir boards were 6.2 mm when working with new knife condition. Geometric mean of the different conditions (after SH test, SS test, and LS test) were 5.9, 6.1, and 6.5 mm, respectively. ANOVA showed that there were no significant differences between the particle size of different control tests (P=0.341, Figure 6). Futhermore, average comminuting time (3.1 ± 0.1 sec) was statistically the same ($P > 0.05$).

The decision to evaluate knife wear was determined by the availability and cost of replacement knives in this study. During the experiement, we chipped almost 60 GmT of stem-wood which varied in size, density, and moisture content. The manufacturer explained how tungsten alloy knives would stay sharp for approximately 1,000 hours of operation before needing a resharpen [59]. Thus, with the small number of operating hours (< 20 hours), we believed that there was no significant effect of knife sharpness on productivity, cost, and feedstock quality of sawdust during the comminution process.

Conclusion

Particle size is an important feedstock characteristic to consider when providing feedstock for biomass conversion processes such as densification, gasification, and torrefaction. In this study, a controlled experiment was performed to evaluate the effect three different material types (small-diameter processed hardwood and softwood, and large-diameter processed softwood) had on a 298-kW sawdust machine's productivity. Feedstock quality, measured by moisture content, particle size, and bulk density, were also characterized.

The average productivity when chipping processed forest residues with this machine was 21.6 BDmT/PMH at a cost of US $4.6/BDmT. Small softwood materials had a 10% higher chipping productivity than small hardwood. Moisture content also had an influence on the geometric mean particle size of sawdust because moisture content influences mechanical stem hardness and strength. Sawdust size increased when material moisture content decreased. The geometric mean particle lengths of chips produced in the study were significantly influenced by the different stem diameter. The bulk density has been found to not have an impact on moisture content.

Knife wear, which was considered a potential confounding variable in the study, was not a significant factor influencing productivity, cost, and feedstock quality in this limited duration trial. In other words, the sharpness of the tungsten alloy knives did not noticabley change the particle size of chips after comminuting 60 GmT of stem wood at a 30% moisture content.

This study's findings have shown that this track-based sawdust machine can be a cost effective option if you are interested in producing small chips like sawdust. Converting stem wood into sawdust-like chips using a mobile machine can effectively support the efforts of converting forest biomass into biobased products such as briquets, wood pellets, and torrefied wood chips as well as composting materials. Further research is need to compare the unique mobile chipper with a 294-kW (400-hp) with a 441-kW (600-hp) engine to find the productivity and feedstock quality from various wood material types.

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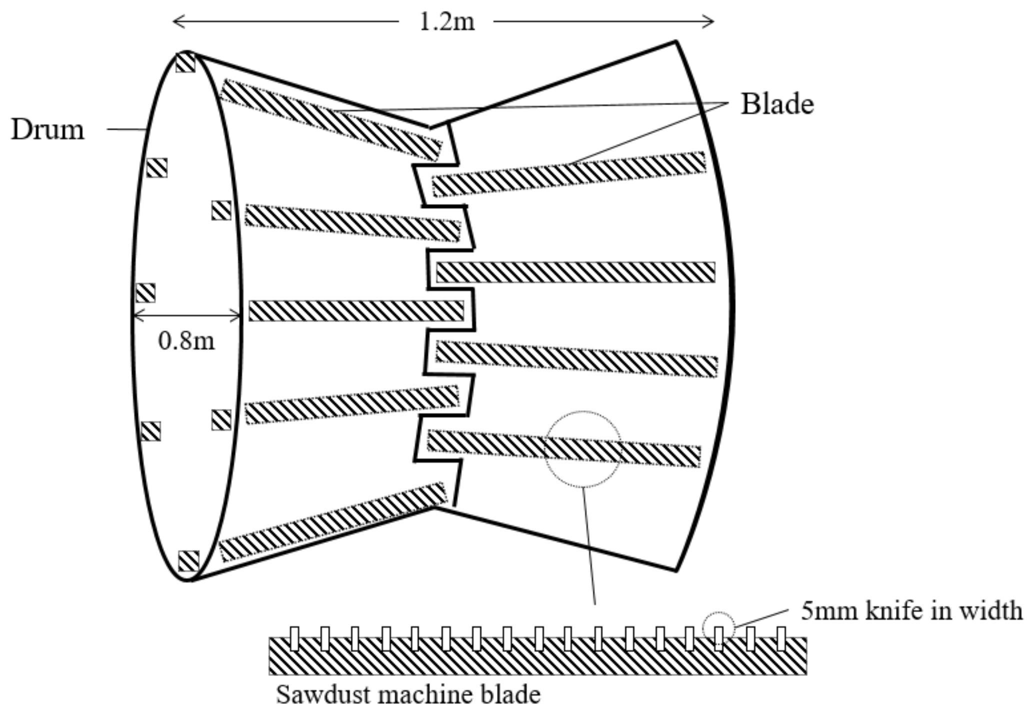


Figure 1. The principle of a sawdust machine drum and knives. The drum carries 18 -19 rows of 37 blades. Rows are equally spaced on the drum surface. The blades is equipped 16-17 knives of 5mm. The sawdust machine version carries 582 knives in the drum.

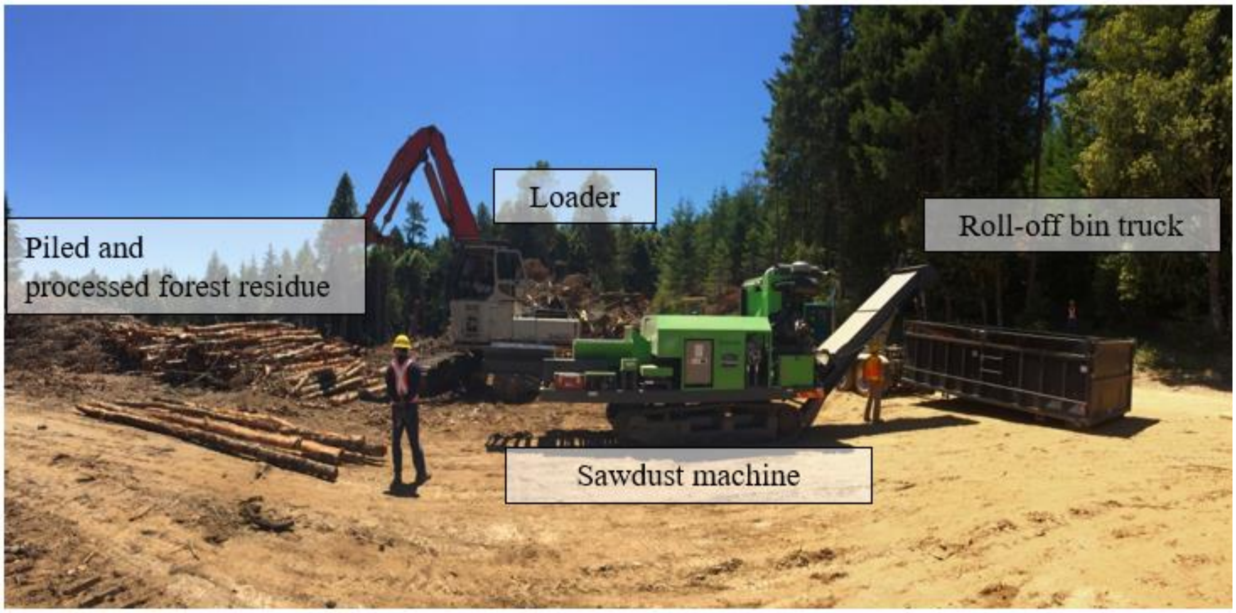


Figure 2. Overview of the sawdust machine testing. The loader fed the left side of the sawdust machine and sawdust was conveyed up the ramp on the right side of the machine into a bin. The sawdust machine required an operator, to monitor the drum's revolutions per minute and control the in-feed conveyor.

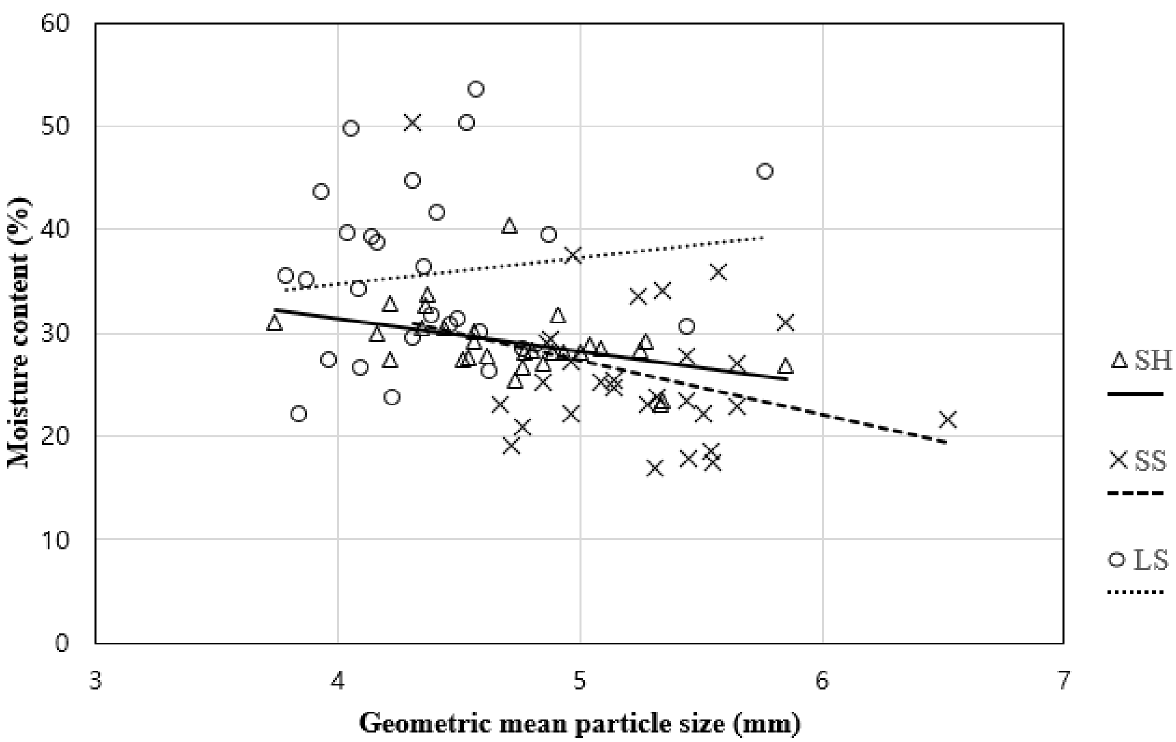


Figure 3. Moisture content, which was calculated using dry oven method, of small diameter hardwood (SH), small diameter softwood (SS), and large diameter softwood (LS) sawdust samples

and their relationship with geometric mean particle size. The moisture content had a moderate correlation with geometric mean particle length on SH (R=−0.43, n=30) and SS (R=−0.48, n=30) trial tests and no pattern correlation in LS (R=0.05, n=30) trial by Pearson's correlation tests.

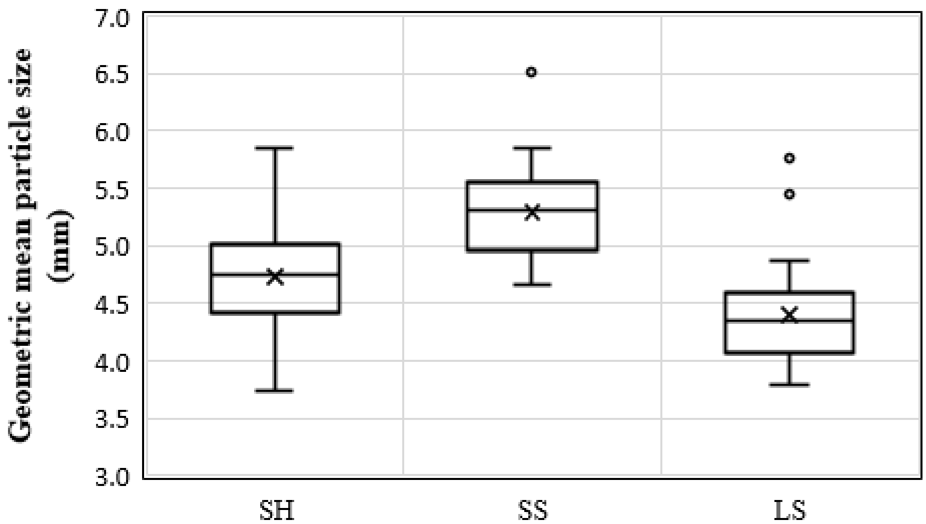


Figure 4. Box and whisker plots of geometric mean particle size among the material types; small diameter hardwood (SH), small diameter softwood (SS), and large diameter softwood (LS). The circles are outliers and the line and X are mean value.

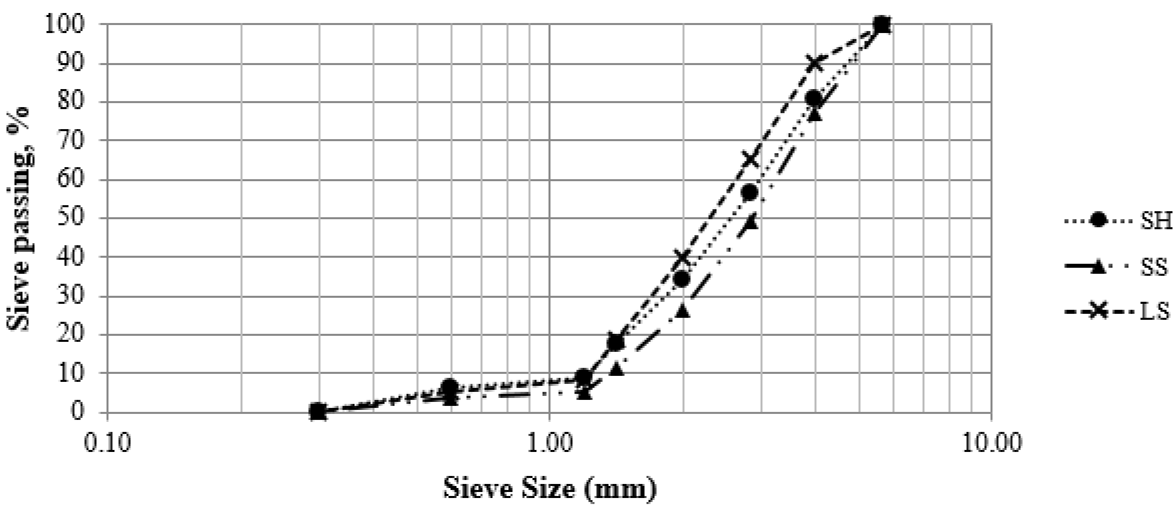
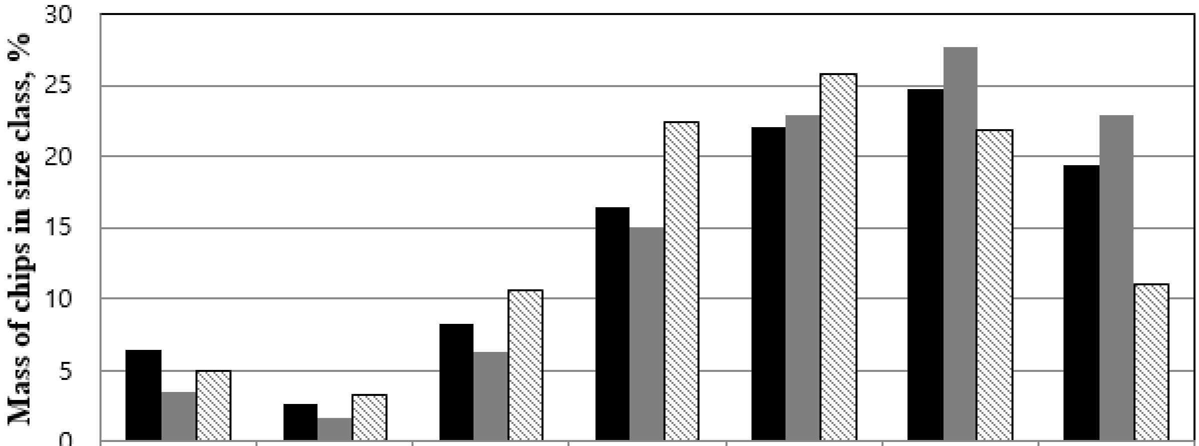


Figure 5. Cumulative size distribution of percentage processed small diameter hardwood (SH), small diameter softwood (SS), and large diameter softwood (LS) sawdust mass passing through screening sieves. The tungsten alooy knives were not influence productivity and feedstock quality during the 60 green metric ton (GmT) comminuting process.



(mm)	<0.84	0.84-1.00	1.00-1.41	1.41-2.00	2.00-2.80	2.80-4.00	>4.00
SH	6	3	8	16	22	25	19
SS	4	2	6	15	23	28	23
LS	5	3	11	22	26	22	11

Figure 6. Size distribution of sawdust samples collected from small diameter hardwood (SH), small diameter softwood (SS), and large diameter softwood (LS) test. The percentage of total sawdust mass captured by 1.19, 1.41, 1.99, 2.83, 3.96, 5.66 mm sieve and a bottom pan.

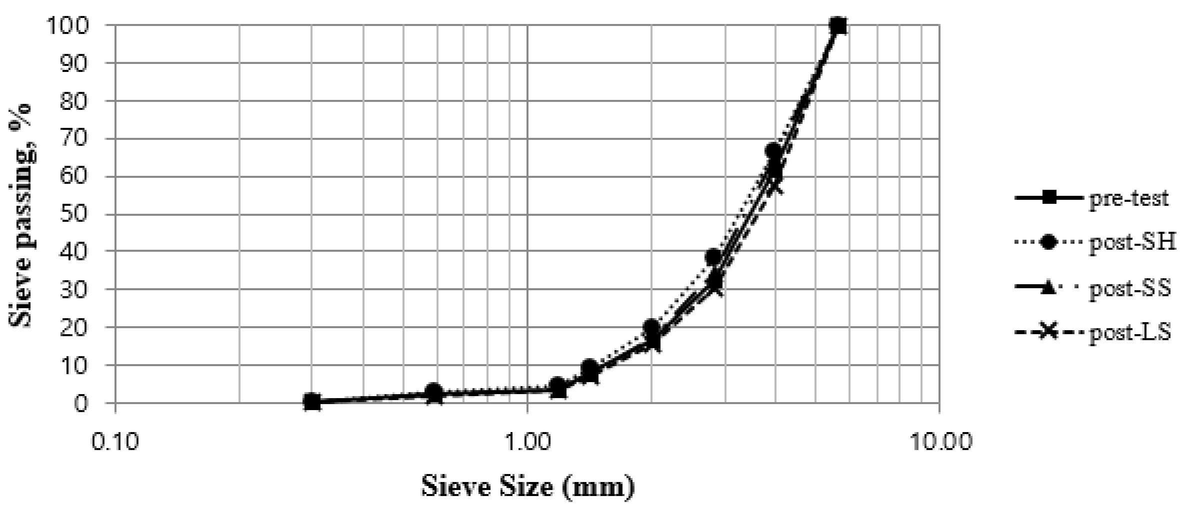


Figure 7. Cumulative size distribution of communited Douglas-fir boards as a control material, before the test with a new knife set (pre-test), post-small-diameter hardwood test (post-SH), post-small-diameter softwood test (post-SS), and post-large-diameter softwood (post-LS).The distribution show the percent mass of Douglas-fir sawdust passing through screening sieves. If the knives were worn during the test, cumulative size distribution of line graph would shift from pre-test line to right.

Table 1. Characteristics, productivity, and cost of materials used to comminute chipper machine operation. Moisture content, productivity, cost, and fuel consumption of small diameter hardwood (SH, < 20cm), small-diameter softwood (SS, < 20cm), and large-diameter softwood (LS, 20 - 30cm) test using a sawdust chipping machine.

	SH	SS	LS
Diameter1 [a] (cm)	18	18	24
Diameter2 [b] (cm)	11	16	21
Length (m)	6	6	7
Stem volume (m^3)	0.14	0.16	0.30
Moisture content (%)	29	27	36
Geometric mean particle size (mm)	4.7	5.3	4.4
Bulk density [c] (kg/m^3)	281	234	269
Avg. cycle time (sec/piece)	22.1	24.7	41.2
Productivity (BDmT[d]/PMH[e])	19.8	18.3	26.7
Fuel consumption (liters/PMH)	27.3	25.9	28.6
Total cost (US $/BDmT)[f]	4.9	5.3	3.6

[a] large-end diameter
[b] small-end diameter
[c] wet-basis bulk density
[d] bone dry metric ton
[e] productive machine hour
[f] loader cost to feed machine not included

Table 2. Summary of assumptions used to estimate hourly machine cost of a 294-kW sawdust machine used in this study.

Cost factors	Sawdust machine
Purchase price (US $)	350,000
Salvage value (% purchase price)	20
Economic life (years)	5
Wage including benefits [a] (US $)	33.25
Crew	1
Fuel consumption (liters/hour)	27
Machine utilization rate (%)	75
Machine cost [b] (US $/PMH)	95.90

[a] sawdust machine operator : 1 crew
[b] productive machine hour

Table 3. Number of 17.6 liter samples collected for each material type.

Material type	Number of samples / Roll-off bin truck		
	Subunit 1	Subunit 2	Subunit 3
Small diameter hardwood	10	10	10
Small diameter softwood	10	10	10
Large diameter softwood	10	10	10
Control material (Douglas-fir board)			
Before small-diameter hardwood test		5	
Before small-diameter softwood test		5	
Before large-diameter softwood test		5	
After large-diameter softwood test		5	
Total		110	