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Research paper

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

Eunjai Lee [a,*], Joel A. Bisson [b], Han-Sup Han [b]

[a] Seoul National University, Department of Forest Sciences, Seoul 08826, South Korea
[b] Humboldt State University, Department of Forestry and Wildland Resources, Arcata 95521, CA, USA

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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 material 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 and 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 and 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.

1. 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 [1–4].

Grinding, which produces hogfuel by hammering material into smaller pieces 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 indiscriminantly 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 [17–19]. A feedstock's

* Corresponding author.
E-mail addresses: ejay0512@gmail.com (E. Lee), Joel.Bisson@humboldt.edu (J.A. Bisson), Han-Sup.Han@humboldt.edu (H.-S. Han).

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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 and 900 °C, 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 and 300 °C [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 [28,29,30], 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 °C. 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 (2–4 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 material 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.

2. Methods and materials

2.1. 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 6–7 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 (2–4 mm) (Fig. 1). At the beginning of the experiment new knives were installed. The machine was equipped 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 (see Fig. 2).

2.2. 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