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Performance of a Mobile Star Screen to Improve Woodchip Quality of Forest Residues

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Abstract: Low harvesting costs and increasing demand for forest-derived biomass led to an increased use of full-tree (FT) harvesting in steep terrain areas in Austria. Logging residues, as a by-product of FT harvesting, present an easily accessible bioenergy resource, but high portions of fine particles and contaminants like earth particles and stones make them a complex and difficult fuel, as they affect storage capability, conversion efficiency, or emission rates adversely. The present research focuses on the productivity and performance of a star screen, which was used to remove fine and oversize particles from previously chipped, fresh Norway spruce (*Picea abies* (L.) Karst.) logging residue woodchips. Three screen settings, which differed in terms of different rotation speeds of the fine star elements (1861 rpm, 2239 rpm, 2624 rpm) were analyzed. Time studies of the star screen were carried out to estimate screening productivity and costs. Furthermore, 115 samples were collected from all material streams, which were assessed for particle size distribution, calorific value, ash content, and component and elemental composition. Average productivity was 20.6 tonnes (t) per productive system hour (PSH_{15}), corresponding to screening costs of 9.02 €/t. The results indicated that the screening of chipped logging residues with a star screen influenced material characteristics of the medium fraction, as it decreased the ash content, the incidence of fine particles, and the nutrient content. The different screen settings had a noticeable influence on the quality characteristics of the screening products. An increase of the rotation speed of the fine stars reduced screening costs per unit of screened material in the medium fraction, but also lowered screening quality.

Keywords: screening; logging residue; woodchips; quality; cost; productivity

1. Introduction

About 47% of the Austrian land area is covered by forests [1], whereof 22% of the forest area is characterized by terrain slopes greater than 60% [2]. On such steep slopes, ground-based harvesting systems, even equipped with traction winches, often reach their physical and ecological limits [3]. Hence, cable-based harvesting systems, using tower yarders for extracting timber from the forest stand to the forest road, are still widely used in steep terrain harvesting. Common harvesting methods are cut-to-length (CTL), tree-length (TL), and full-tree (FT) harvesting. Until the 1990s, motor-manual CTL systems, where the trees are felled, delimbed, and bucked manually to assortments of varying lengths within the stand, were widely used in steep terrain harvesting. The development of processor heads with gripping capabilities in the early 1990s resulted in an increased use of FT harvesting systems, in which the trees are delimbed and bucked at the roadside. Heinimann et al. [4] estimated that the mechanization of tree processing results in cost savings of about 40%. Today, processor tower yarders working with FT harvesting represent the state-of-the-art technology in steep terrain harvesting in Central Europe.

However, the increased use of FT harvesting involves a greater removal of nutrients from the harvesting site, as the tree parts with the highest nutrient content, needles and twigs, are largely removed from the site. Consequently, several studies [5–8] dealing with possible impacts of FT harvesting on site productivity were conducted all around the world. The conclusions of the studies were somewhat different: several studies have found significant negative impacts of FT harvesting on site productivity [5,6], while another did not observe any negative impacts [8]. In general, it seems that the impact of FT harvesting on soil productivity mainly depends on the forest and soil type.

During FT cable yarding operations, branches and non-merchantable tops (logging residues) are piled next to the forest road. The current options for brush piles in Central Europe are either: (i) to leave them on site to decay or (ii) to use them for energy production. Analysis on changes of the nutrient distributions around remaining brush piles showed that nutrient release is limited to the vicinity of the remaining piles [9]. Given the fact that extraction distances in cable yarding operations are quite often longer than 200 m, the impact of remaining brush piles as a nutrient source for the entire forest stand can be ignored. Within the last few years, the utilization of brush piles gained importance due to the fact that political and social pressures are continually increasing the need for renewable energy sources. Nevertheless, the use of logging residues as an energy source still plays a minor role due to great variability in its product characteristics (particle size, ash content, moisture content, etc.) [10] and higher procurement costs compared to sawmill by-products [11]. Hence, to further promote the use of logging residues, it is necessary to both reduce procurement costs by optimizing supply chain management and to achieve higher selling prices by increasing product quality [11,12].

Green chips (woodchips made of fresh logging residues including branches and tops) are a very heterogeneous material, which make them a complex and difficult fuel due to their high variability in terms of material composition and characteristics. Their quality varies strongly according to tree, site, and stand characteristics, harvesting season, and silvicultural treatment [13]. Moreover, logging residue woodchips as a primary source of biomass fuel are characterized by irregular particle size and shape, high moisture content, low bulk density, and the presence of contaminants (earth, stones), which affect its storage capabilities and application possibilities [10]. Small and medium sized heating plants are especially sensitive to biomass fuels of different poor quality. In contrast to industrial users, they usually require woodchips with low moisture content and small particle lengths [14].

Particle size distribution is one of the most important woodchip characteristics influencing conversion efficiency and emission rates [15]. The removal of fine particles increases storage stability, as it favors air circulation inside the pile, which hampers spore formation and accelerates the drying process. On the other hand, the removal of oversize particles reduces the risk of bridging or arching, which is especially problematic in small heating plants, whose conveying ducts are relatively small and can be blocked easily by long particles [16].

Recently, some studies have examined methods that could improve wood biomass characteristics to meet the product quality required by heating plants. While some studies focused on different chipper or grinder settings [17–19], others dealt with different screening machines, which are used to improve the quality of woodchips [14,20–23]. Although all studies concluded that it is possible to significantly increase fuel quality by screening, screening before combustion is still only performed occasionally.

After screening, the medium sized particles are directly transported to an energy facility, while the coarse particles usually require further chipping before combustion. The fine particles can either be discharged in the forest or transported to a composting plant. Alternatively, a completely new approach would be to return the fine particles to some forest sites in order to reduce the ecological impact of utilizing logging residues for energy production by increasing the nutrient pool of some sites [24].

Studies on screening performance are infrequent and mainly focused on quality improvements of woodchips. Furthermore, little is known about nutrient and tree part composition of the rejected fines, which are crucial factors needed to evaluate the suitability of this material for composting or field application. The aim of this study was to analyze the performance of a star screen specifically designed to remove fine and coarse size particles in order to increase woodchip quality, operating with three different machine settings. In particular, the study aimed to determine: (i) the material properties of untreated chips from fresh cable yarding brush piles; (ii) the productivity and the cost of the screening process; (iii) the obtained quality improvement of the logging residue woodchips; and (iv) the suitability of separated fines in terms of physical and chemical characteristics to be either composted or returned to the forest site as a nutrient source.

2. Materials and Methods

A mobile drum chipper (Albach Silvator 2000) was used to comminute fresh logging residue piles (time since harvest was shorter than 20 days) after different FT cable yarding operations. The chipper was equipped with 12 chipping knives, which had been sharpened at the beginning of the chipping operation. All logging residues originated from pure Norway spruce (*Picea abies*) stands. In total, brush piles from 11 thinning and 12 clear-cut operations were used within this study. The chipper was equipped with 12 chipping knives and a 100-mm sieve. At the roadside, the chips were blown directly into container trucks, which transported the chips to a terminal station, where the chips were screened within the next three days.

A mobile star screen ″Multistar L3″, developed in Austria by the company "Komptech" (Figure 1), was used to separate fresh logging residue woodchips into three fractions (fine, medium, coarse). The machine was powered by a 60-kW diesel engine and was located at a bituminized terminal station. The main machine characteristics are presented in Table 1.

Figure 1. Mobile star screen "Multistar L3" fed by a wheeled front-end loader.

Table 1. Main machine characteristics of the star screen.

Manufacturer	Komptech GmbH
Model	Multistar L3
Year of manufacture	2009
Engine type	diesel generator
Engine power	60 kVA
Weight (transport position)	ca. 19 t
Dimensions in transport position (L × W × H)	11.3 × 2.6 × 4.0 m
Dimensions in working position (L × W × H)	12.8 × 6.3 × 4.0 m
Hopper volume	ca. 7 m^3
Coarse screen dimensions (L × W)	3.2 × 1.3 m
Fine screen dimensions (L × W)	5.8 × 1.3 m
Max. throughput capacity	180 m^3/h

Material was deposited onto the screen by a wheeled front-end loader, which poured the fresh woodchips inside the 7-m^3 hopper of the screen (Figure 2). Inside the hopper, a scraper floor continuously conveyed the material to a dosing roller, which distributed the woodchips consistently onto the coarse screen deck. This deck consists of many robust, rotating star-elements, which are arranged in multiple rows. The stars were made of rubber and feature a cleaning finger that clears the screening gap to the surrounding stars at each rotation in order to prevent material blockage. Oversize particles make it all the way to the end of the screening deck, whereas smaller particles fall through the spacings between the stars onto a conveyor belt, which delivers them to the fine star deck. In contrast to the coarse screen deck, the rubber stars of the fine deck are much smaller and more elastic. Commercial, medium sized woodchips make it all the way to the end of the fine screen deck, whereas fine particles fall through the spacings between the stars.

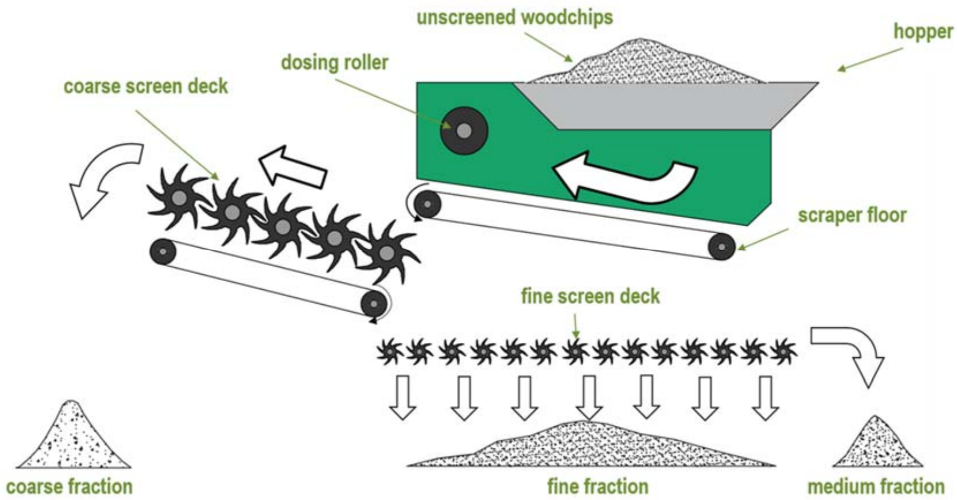

Figure 2. Simplified operating principle of a star screen.

Three different screen settings were analyzed within this study: The rotation speed of the hydraulic engine, which powers the stars at the fine screen deck, was set to either 1861 rpm (62% of maximum speed), 2239 rpm (74% of maximum speed), or 2624 rpm (87% of maximum speed), whereas all other screen settings (speeds of scraper floor, dosing roller, and stars of the coarse screen deck) were kept constant during the whole study time. The hydraulic engine, which powers the scraper floor and the dosing roller at the same time, was set to 880 rpm, and the rotation speed of the engine that powers the stars of the coarse screen deck was set to 2415 rpm. The different screen settings of the fine screen deck were selected based on recommendations of the manufacturer, the experience of the machine owners, and the results of test runs (optical inspection of screening products at different settings). The fresh logging residue woodchips, which derived from different harvesting operations, were assigned randomly to the three different settings of the fine screen deck. In total, six treatments (Table 2) were examined with variables including rotation speeds of the stars and harvest type (thinning, clear-cut).

Table 2. Treatment block.

Setting of the Fine Screen Deck	Harvest Type	Number of Harvesting Sites Sampled
1861 rpm (62% of Max. Speed)	Thinning	4
	Clear-cut	4
2239 rpm (74% of Max. Speed)	Thinning	3
	Clear-cut	4
2624 rpm (87% of Max. Speed)	Thinning	4
	Clear-cut	4

2.1. Product Analyses

At the terminal, woodchips of the 23 harvesting sites were piled separately to be able to distinguish between the different treatments. Four material streams were sampled at the beginning, at the middle, and at the end of each screening operation: the unscreened material, the fine fraction, the medium fraction, and the coarse fraction. At each screening operation, all three samples of the same material stream were combined to one composite sample to produce a representative sample of each material stream of a given woodchip pile. From each of these composite samples, a ca. 16-L sample was bagged, labeled, and immediately weighed on-site to determine the initial mass. Subsequently, the samples were oven dried in the laboratory at 105 °C to a constant mass. Dry masses were compared with the corresponding initial masses in order to estimate moisture content at a wet basis according to international standards [25]. The reported values within this study are an average of two measurements.

The dried samples were further analyzed for particle-size distribution [26], component composition, heating value [27], ash content [28], and elemental composition [29]. Therefore, each sample was separated into five sub-samples with different masses.

Mechanical particle size distribution was analyzed using a one-dimensional horizontal sieve shaker (GFL 3016). The sieve shaker was set to an amplitude of 30 mm and a frequency of 300 rpm. Seven classification sieves with square holes (Ø 400 mm) were used to determine particle-size distribution: 63 mm, 45 mm, 31.5 mm, 16 mm, 8 mm, 3.15 mm, and 1 mm. For simplicity, the different fractions were grouped into three functional classes: fines (<3.15 mm), acceptable (3.15 mm–63 mm), and oversize particles (>100 mm).

Component composition was determined on 100 g (fine fraction) to 1000 g (coarse fraction) sub-samples by sorting them manually into the following groups: fibers, bark, branches, needles, dust, and others (e.g., stones and other inorganic materials). Particles smaller than 0.75 mm were principally assigned to dust because it was impossible to assign them to a specific group without doubt.

Sub-samples of ca. 100 g were taken from each composite sample to determine the calorific value and the ash content. A "Retsch SM100" cutting mill, equipped with a 1-mm sieve, was used to comminute the sub-samples roughly. A "Retsch GM200" knife mill was further used to comminute the samples to a particle size of at least 1 mm. One gram of the samples was pressed to pellets with a "Parr manual press" before it was burned in an "IKA C200" bomb calorimeter. Another previously milled sub sample of ca. 3 g was used to determine the ash content according to international standards [28].

One-way ANOVA and samples t-tests were performed using the SPSS 21 statistical package (IBM Corp., Chicago, IL, USA) to determine significant differences between treatments. Statistical differences at an alpha level of 0.05 indicated product differences for a number of categories between treatments. The Bonferroni method was used to adjust *p*-values for multiple comparisons.

2.2. Production and Cost Analyses

Net weight of each loaded truck was recorded at delivery to the terminal station at a weigh-bridge. During screening, the fine and coarse fraction were directly discharged into containers (see Figure 1), which were also weighed at the terminal station directly after each screening cycle. The mass of the medium fraction was calculated by subtracting the net-mass of the fine and coarse fraction from the mass of the unscreened material.

The time study consisted of 23 woodchip piles, each consisting between 5.68 and 26.43 tonnes of green chips. Each pile originated from different FT cable yarding operations close to the city of Leoben, Styria in Austria (47°12′45.3″ N, 14°51′14.6″ E). The time study was carried out manually using a portable handheld computer (AlGiz 7, Handheld, Lidköping, Sweden). The working time was recorded at a cycle level by applying a continuous timing method. The observation unit was the screening of one whole chip pile. Overall working time of the star screen was divided into effective working time (PSH_0) and delay times. Effective working time was defined as the time span in which material was delivered from the hopper to the coarse screen deck.

The calculation of the machine costs was conducted with a few modifications according to the Scheme of Food and Agriculture Organization of the United Nations [30]. The following assumptions were made (Table 3): According to information from local dealers, the investment costs are ca. 350,000.00 € for the star screen and ca. 165,000.00 € for the wheel loader. The annual utilization rates for both the wheel loader and the star screen were set to 1000 PMH_{15} (productive machine hours per year, including delays up to 15 min) each. The annual interest costs were calculated at an interest rate of 5.0%. The depreciation period was assumed to be 10 years. Repair and maintenance costs for the star screen and the loader were estimated to be 26.25 €/PMH_{15} and 8.79 €/PMH_{15}, respectively. Fuel consumption of the machines was calculated using a fuel price of 1.20 €/L and the net power of the machines. The lubricants costs were assumed to be 25% of the fuel costs. To run the whole system, only one worker was required to operate the wheel loader. The labor costs including wages were set to 30 €/PMH_{15}. All calculations were made without sales tax.

Table 3. Cost assumptions and calculated machine costs.

	Star Screen (Multistar L3)	Wheel Loader (Volvo L110H)	Unit
Input Data			
Purchase price	350,000.00	165,000.00	€
Expected useful life	10,000	13,000	PMH_{15}
Technical obsolescence	10	10	Years
Annual utilization	1000	1000	PMH_{15}
Utilization barrier	1000	1300	PMH_{15}
Interest rate	5.0	5.0	%
Repair cost ratio	0.75	0.90	
Material Costs			
Interest	8.75	4.13	€/PMH_{15}
Insurance	3.40	3.80	€/PMH_{15}
Depreciation	35.00	16.50	€/PMH_{15}
Repair costs	26.25	8.79	€/PMH_{15}
Fuel costs	10.08	27.36	€/PMH_{15}
Lubricant costs	2.02	5.47	€/PMH_{15}
Total Material Costs	85.50	66.05	€/PMH_{15}
Labor Costs	0.00	30.00	€/PMH_{15}
Total Machine Costs	85.50	96.05	€/PMH_{15}
Total System Costs	181.55		€/PSH_{15}

Note: PMH_{15} = Productive Machine Hours, including delays up to 15 min; PSH_{15} = Productive System Hours, including delays up to 15 min.

3. Results

3.1. Productivity and Cost

Figure 3 shows the resulting amounts of the different material streams after screening. The mass fraction of screening rejects (fines and coarse fraction) varied in the range of 20.2% to 41.2%, depending on the screen settings. The results clearly show that a reduction in rotation speed of the fine stars leads to a significantly higher amount of screening rejects and lowers the amount of material in the medium fraction. However, a change of the rotation speed of the fine stars does not influence the amount of the rejected coarse fraction. The mass of the fine and the medium fraction all differed significantly from each other ($p < 0.050$) at the three different fine screen settings analyzed within this study.

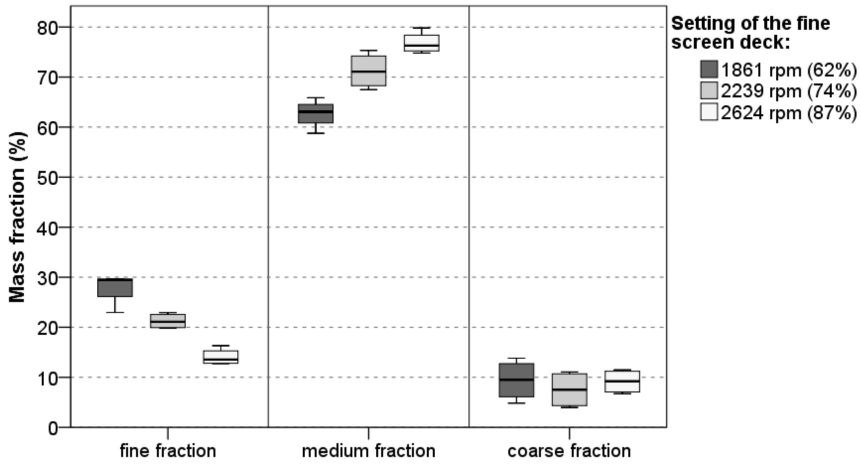

Figure 3. Mass fraction in percent after screening application for the tested fine screen settings.

The average gross productivity of the tested machines was 20.99 t/PSH_0 (Table 4). During the time study, few delay times were observed. Delay times of less than 15 min amounted to 1.02% of the total PSH_{15}. Almost all delay times were related to human caused operational errors, which occurred at the beginnings of the first screening cycles.

Table 4. Productivity and cost of screening logging residue woodchips. The presented results were calculated based on the amount of unscreened woodchips.

	Unit	Mean	SD
Moisture content	%	44.58	1.44
Productivity	t/PSH_0	20.99	2.75
	t/PSH_{15}	20.62	3.27
	m^3 (loose)/PSH_0	143.74	18.87
	m^3 (loose)/PSH_{15}	141.20	22.37
Costs	€/t	9.02	1.47
	€/m^3(loose)	1.32	0.21

Note: PSH_0 = Productive Machine Hours, excluding all delays; PSH_{15} = Productive System Hours, including delays up to 15 min.

Machine cost calculation showed that the total costs of the observed system (star screen and wheel loader) are 182 €/PSH_{15} (Table 3). Using a given system productivity of 20.99 t/PSH_{15}, total screening costs amount to 9.02 €/t, based on the amount of unscreened chips.

3.2. Product Analyses

The mean incidence of the tree components under different fine screen settings before and after screening is shown in Table 5. Before screening, the fresh logging residue chips contained 55.6% of fibers, 15.1% of needles, 14.5% of bark, 10.8% of twigs, and 4% of "others" (very small particles and contamination with inorganic particles), on average. The unscreened material did not differ significantly in terms of component composition between the different treatments. After screening, the needle content of the medium fraction was significantly lower than that of the unscreened material at rotation speeds of 1861 and 2239 rpm. However, no significant reduction of the needle content was found at a rotation speed of 2624 rpm. The results further indicated that screening seemed to increase the amount of fibers and lower the proportion of contaminants and very small particles (category "others"), but these differences were not significant in statistical terms. The fine fraction represented the pile with the highest needle and lowest fiber content. The proportions of both components differed significantly from the unscreened material.

Table 5. Fiber, bark, twig, and needle contents of the woodchip samples (%) before and after screening.

			Unscreened Woodchips	Screened Fraction		
				Fine	Medium	Coarse
Setting of the Fine Screen Deck	1861 rpm (n = 8)	Fibers	58.23 ^{a}	18.27 ^{b}	69.16 ^{ac}	78.79 ^{c}
		Bark	13.22 ^{a}	15.29 ^{a}	12.87 ^{a}	7.85 ^{a}
		Twigs	11.75 ^{a}	6.02 ^{a}	9.68 ^{a}	10.94 ^{a}
		Needles	13.32 ^{a}	52.93 ^{b}	5.84 ^{c}	1.43 ^{d}
		Others	3.48 ^{a}	7.48 ^{b}	2.46 ^{a}	0.99 ^{a}
	2239 rpm (n = 7)	Fibers	58.70 ^{a}	13.17 ^{b}	62.99 ^{ac}	76.47 ^{c}
		Bark	15.56 ^{a}	12.44 ^{a}	16.66 ^{a}	12.63 ^{a}
		Twigs	8.19 ^{a}	5.48 ^{a}	11.76 ^{a}	8.10 ^{a}
		Needles	14.07 ^{a}	52.62 ^{b}	6.09 ^{c}	1.92 ^{d}
		Others	3.49 ^{a}	16.29 ^{b}	2.50 ^{ac}	0.88 ^{c}
	2624 rpm (n = 8)	Fibers	50.16 ^{a}	9.93 ^{b}	48.78 ^{a}	68.62 ^{a}
		Bark	14.98 ^{a}	13.33 ^{a}	11.81 ^{a}	9.81 ^{a}
		Twigs	12.17 ^{ab}	4.03 ^{a}	17.57 ^{b}	16.10 ^{ab}
		Needles	17.68 ^{a}	59.64 ^{b}	17.38 ^{a}	3.58 ^{c}
		Others	5.02 ^{a}	13.06 ^{b}	4.47 ^{a}	1.89 ^{a}

Note: Values represent % incidence on total sample mass (on a dry basis); Values in the same row not sharing the same supscript letter are significantly different at $p < 0.05$ in the equality for column means.

Screening seems to improve particle size distribution by increasing the proportion of acceptable particles and decreasing that of fine and oversize particles (Table 6). However, the quality of removing fines and oversize particles largely depended on the screen settings. The usage of a fine screen setting of 1861 rpm led to the highest proportion of acceptable particles (84.4%) in the medium fraction, which differed significantly from that of the unscreened material (69.1%). Treatments with higher rotation speeds were not able to significantly increase the proportion of acceptable particles compared with the unscreened woodchips. Fines were particularly abundant in the fine fraction, representing 69% to 81% of its total mass. However, it was not possible to remove all fine particles from the woodchips. Only at a fine screen setting of 1861 rpm could a significant reduction of the fine particles from 22.9% to 8.4% be observed.

Table 6. Particle size distribution of the woodchip samples before and after screening.

				Fines, % (<3.15 mm)	Acceptable, % (3.15–63 mm)	Oversize, % (>63 mm)
Setting of the Fine Screen Deck	1861 rpm (n = 8)	Unscreened Woodchips		22.86 ^{a}	69.06 ^{a}	8.09 ^{a}
		Screened	Fine fraction	71.78 ^{b}	28.22 ^{b}	0.00 ^{a}
			Medium fraction	8.44 ^{c}	84.42 ^{c}	7.15 ^{a}
			Coarse fraction	1.90 ^{c}	49.26 ^{d}	48.85 ^{b}
	2239 rpm (n = 7)	Unscreened Woodchips		22.24 ^{a}	68.19 ^{ac}	9.58 ^{a}
		Screened	Fine fraction	69.10 ^{b}	30.90 ^{b}	0.00 ^{a}
			Medium fraction	8.97 ^{ac}	80.92 ^{a}	10.11 ^{a}
			Coarse fraction	2.14 ^{c}	54.07 ^{c}	43.79 ^{b}
	2624 rpm (n = 8)	Unscreened Woodchips		25.93 ^{a}	66.71 ^{a}	7.35 ^{a}
		Screened	Fine fraction	80.56 ^{b}	19.44 ^{b}	0.00 ^{a}
			Medium fraction	23.88 ^{a}	71.16 ^{a}	4.83 ^{a}
			Coarse fraction	5.55 ^{c}	53.15 ^{c}	41.29 ^{b}

Note: Values represent % incidence on total sample mass (on a dry basis); Values in the same column not sharing the same supscript are significantly different at $p < 0.05$ in the equality for column means.

Moisture content was calculated for the unscreened woodchips directly before and for the three screened fractions directly after screening (Table 7). The average moisture content of the green, unscreened chips was 44.6%. There was no significant difference in moisture content of the unscreened chips between the treatments before screening. However, differences were detected between the different fractions after screening. At all screen settings, the moisture content of the coarse fraction was significantly lower than that of the fine and medium fraction. Moisture content was always highest at the fine fraction.

Table 7. Moisture, ash, energy, and nutrient contents before and after the screening operations.

			Unscreened	Screened Fraction		
				Fine	**Medium**	**Coarse**
Setting of the Fine Screen Deck	**1861 rpm** (n = 8)	Moisture content (%)	46.42 ^{ab}	56.97 ^{a}	52.09 ^{a}	41.41 ^{b}
		Ash content (%)	2.70 ^{a}	7.65 ^{b}	2.36 ^{a}	1.29 ^{a}
		Energy content (MJ/kg)	20.6 ^{a}	20.4 ^{a}	20.7 ^{a}	20.6 ^{a}
		Nutrient content:				
		C (%)	51.1 ^{a}	47.8 ^{b}	52.4 ^{c}	52.6 ^{c}
		N (ppm)	3727 ^{a}	7139 ^{b}	2963 ^{ac}	2477 ^{c}
		P (ppm)	300 ^{a}	543 ^{b}	241 ^{a}	223 ^{a}
		K (ppm)	1094 ^{a}	1614 ^{b}	948 ^{a}	1082 ^{a}
		Ca (ppm)	3954 ^{a}	6147 ^{b}	3701 ^{a}	3157 ^{a}
		Mg (ppm)	511 ^{a}	781 ^{b}	483 ^{a}	403 ^{a}
	2239 rpm (n = 7)	Moisture content (%)	45.64 ^{ab}	50.97 ^{a}	48.36 ^{a}	42.87 ^{b}
		Ash content (%)	3.56 ^{a}	16.29 ^{b}	2.70 ^{a}	1.41 ^{a}
		Energy content (MJ/kg)	20.4 ^{ab}	19.0 ^{a}	20.5 ^{ab}	20.6 ^{b}
		Nutrient content:				
		C (%)	51.0 ^{a}	47.9 ^{b}	52.2 ^{c}	52.4 ^{c}
		N (ppm)	3708 ^{a}	7777 ^{b}	3193 ^{ac}	2549 ^{c}
		P (ppm)	295 ^{a}	588 ^{b}	271 ^{a}	231 ^{a}
		K (ppm)	1086 ^{a}	1708 ^{b}	1056 ^{a}	1116 ^{a}
		Ca (ppm)	4111 ^{a}	6223 ^{b}	4248 ^{a}	3687 ^{a}
		Mg (ppm)	512 ^{a}	841 ^{b}	532 ^{a}	433 ^{a}
	2624 rpm (n = 8)	Moisture content (%)	41.80 ^{a}	55.62 ^{b}	52.92 ^{b}	47.11 ^{a}
		Ash content (%)	4.30 ^{a}	10.53 ^{b}	3.34 ^{a}	2.24 ^{a}
		Energy content (MJ/kg)	20.6 ^{ab}	19.6 ^{a}	20.5 ^{ab}	20.7 ^{b}
		Nutrient content:				
		C (%)	50.8 ^{a}	47.7 ^{b}	52.0 ^{c}	52.3 ^{c}
		N (ppm)	4298 ^{a}	8053 ^{b}	4670 ^{a}	3055 ^{c}
		P (ppm)	350 ^{a}	610 ^{b}	384 ^{a}	279 ^{a}
		K (ppm)	1236 ^{a}	1751 ^{b}	1330 ^{a}	1229 ^{a}
		Ca (ppm)	4473 ^{a}	6436 ^{b}	4459 ^{a}	3737 ^{a}
		Mg (ppm)	576 ^{ac}	856 ^{b}	639 ^{a}	481 ^{c}

Note: Values in the same row not sharing the same supscript are significantly different at $p < 0.05$ in the equality for column means.

The ash levels corresponding to each screening level and screen setting are of primary concern for evaluating the quality of the material. Screening showed no significant reduction in ash content for all three treatments. The ash content of the fine fraction, however, was significantly higher than that of the unscreened material and the medium and coarse section, ranging from an average of 7.65% at a fine screen setting of 1861 rpm to an average of 16.29% at a fine screen setting of 2239 rpm. For all treatments, the coarse fraction showed the lowest ash contents, which differed significantly from that of the fine fraction, but not from the medium fraction and the unscreened material.

The energy content of the screened medium fraction did not differ significantly from the unscreened material. Differences between the different material streams and the different treatments appear to be very small. The screened fine fraction was shown to contain the lowest energy content, which, however, did not differ significantly from the unscreened material.

Elemental analyses were also performed for the different material streams. The highest nutrient concentrations were found to be in the fine fraction. All analyzed macronutrients of the fine fraction had a significantly higher nutrient concentration than the unscreened material. However, screening only led to a slight reduction of nutrient contents in the medium fraction, which turned out to be non-significant.

3.3. Cost-Benefit Comparison

The rotation speed of the fine stars largely influences the quality of the screened material. High quality woodchips are usually characterized by a low ash content, a high energy content, and a low proportion of fine particles. Moreover, from an ecological perspective, most of the nutrients should be left on the forest site, which means that woodchips should contain low needle and nutrient contents. In our study, these requirements were mostly met at a rotation speed of 1861 rpm. However, even with this setting, the majority of the quality parameters did not differ significantly from the unscreened woodchips.

Generally, the results indicate that a reduction of the rotation speed has a positive impact on the quality of the screened chips (Table 8). At the same time, low rotation speeds led to a reduced discharge of medium fraction chips, resulting in increased screening costs, calculated on the amount of chips of the medium fraction. Differences between screening costs were highest between a rotation speed of 1861 rpm and 2239 rpm. At the same time, the quality improvement by reducing the speed from 2239 rpm to 1861 rpm was comparatively low.

Table 8. Screening costs and selected characteristics of the screened woodchips (medium fraction) corresponding to different settings of the star screen.

	Setting of the Fine Screen Deck		
	(1861 rpm)	**(2239 rpm)**	**(2624 rpm)**
Screening Costs [1] (€/t)	14.05	12.36	11.47
Incidence of Acceptable Particles [1] (%)	**84.42**	80.92	71.16
Av. Energy Content [1] (MJ/kg)	20.68	20.46	20.45
Av. Ash Content [1] (%)	2.36	2.70	3.34
Av. Nitrogen Content [1] (ppm)	2963	3193	4670
Av. Needle Content [1] (%)	5.84	6.09	17.38

[1] Values refer to the amount of screened woodchips (medium fraction) Bold values differ from the unscreened woodchips at a significance level of 5%.

4. Discussion

Our results indicated that the screening of green woodchips with a star screen with the fine screen deck set to 1861 rpm or 2239 rpm can significantly reduce the needle content of the screened medium fraction, which positively influenced material characteristics like ash content and particle size distribution. The highest setting of the fine screen deck (2624 rpm) did not significantly change the needle content relative to the unscreened woodchips.

The ash levels measured with chipped, green woodchips fall within the typical range of the literature [31] and are likely a product of contaminants introduced during harvesting and chipping operations. However, wood ash often comprises high concentrations of heavy metals, which may exceed national limit values for maximum allowable heavy metal concentrations for fertilizers [32] and consequently needs to be brought to a landfill. Thus, from a cost perspective, the amount of ash produced should be minimized in order to decrease both maintenance costs at the heating plants and disposal costs. The present study showed that the use of star screens leads to a reduction of the amount of ash produced by heating plants. At all screen settings, the ash content of the fine fraction was significantly higher than that of the medium fraction. Nevertheless, no significant differences of the ash content between the unscreened and the screened medium fraction could be observed at any screen setting.

For small heating plants, particle size distribution is one of the most important quality parameters because they are very sensitive to fine and oversize particles. Long, irregular particles are often problematic, as they may cause blockages and hinder the firing process. In contrast, fine particles reduce the air circulation within the woodchip piles, which decreases drying speed and increases the risk of self-combustion and spore formation due to microbial activity and fungal infestation [21]. Previous studies on screening machines already have shown that it is possible to remove fine and/or oversize particles [14,20–23]. However, the machines tested within these studies differed in terms of throughput capacity and working principle: trommel screens and vibrating desks are only able to remove fine particles from the material stream, whereas star screens are able to separate woodchips into three fractions. Thus, star screens offer advantages, since they are able to remove fine and oversize particles at once. Nevertheless, the study hints at a substantial reduction of coarse particles (>63 mm). Even after screening, the medium fraction contained 5% to 10% of coarse particles on average, indicating that there is a strong need to adjust the coarse screen settings to obtain less oversize particles at the medium fraction after screening.

Our results indicate that the moisture content of the woodchips may also influence the quality of the screening process in terms of particle size distribution. Within this study, it was not possible to remove all needles, which usually represent small particles that belong to the fine fraction. On average, 20% to 40% of the needles were not detected as fine particles by the screen at the different settings. One cause for this inefficient separation is the fact that green logging residue woodchips constitute a high content of needles, which are mostly still attached to the branches. While some needles fall off the branches during screening, others remain attached and are treated as large particles together with the branches. During drying, the needles start to fall off the branches, which increases the proportion of fines within the piles of the medium and coarse fractions.

Knowing this fact, one could assume that it would be best to let the green chips dry at the terminal before screening. However, this approach would lead to increased drying times of the woodchips, since the high portion of fine particles within the piles hamper air circulation. As a result, higher storage capacities would be required due to both the reduced drying speed of the woodchips and the higher amount of material due to the additional presence of fine and coarse particles within the piles.

Another approach would be to let the logging residue piles dry at roadside landings before chipping and screening. In this case, parts of the needles would fall off the branches and remain at the roadside, reducing the amount of fine particles in the woodchips [33,34]. Furthermore, low moisture contents of the material would lead to a reduction of the procurement costs, since transportation costs are largely influenced by the moisture content of the transported material [35]. However, the drying performance of logging residue brush piles depends on numerous factors such as air humidity, temperature, soil humidity and temperature, precipitation, solar radiation, and airflow velocity [36]. Especially at roadside landings, conditions for drying are often disadvantageous due to shade from surrounding trees [34]. Moreover, high contents of needles and fine branches reduce the airflow velocity within the piles. In particular, there have been a few studies dealing with the drying speed of logging residue piles at roadside landings, which reported different drying performances of brush piles [33,34,37,38]. Stampfer and Kanzian [37] reported that moisture content of logging residue piles decreased from 40–50% to 15–29% during summer, whereas analyses of Nurmi [33] showed only a slight decrease in moisture content from 56% to 42% within one year. However, also in this study, approximately one-third of the needles fell off during roadside storage. Based on these findings, it can be assumed that increased storage times very likely reduce the number of fine particles within the unscreened woodchips and may also facilitate the separation of needles and other fines during screening later on. Consequently, there is a strong need for further research to analyze both the impact of wood storage times and conditions on quality parameters of woodchips and the performance of screens dealing with drier logging residue woodchips.

Operationally, equipment utilization was high within this study—never falling below 90% for both machines, the star screen and the loader. However, it was not possible to make fundamental, reliable estimates of delay times due to the limited observation time of the system (ca. 8 h). More fundamental and accurate statements on delay times can only be obtained by long-term follow-up studies or by combining a larger number of machine category specific time studies [39]. Recent studies on screening machines showed much higher shares of delay times: Spinelli et al. [14] found a total share of delay times of ca. 25% during a time study of a small mechanical screen. The share of delay times during a time study of a grinder/trammel screen system, reported by Dukes et al. [23], was even higher, ranging from 34% to 60% of the total scheduled time. Thus, there is still a strong need to carry out long-term studies on machines that can be used to screen woodchips in order to achieve more reliable estimates of delay times.

From a cost perspective, screening of logging residues increased fuel production costs by 11 to 14 €/t, calculated on the amount of chips of the medium fraction. However, previous studies on other screening machines showed much higher costs. Spinelli et al. [14], who conducted a study on a mobile mechanical vibration screen, reported on total screening costs of 28.5 €/t, whereas Nati et al. [21], who analyzed the performance of a trommel screen, reported on screening costs ranging from 16.2% to 19.9 €/t.

At the time of writing, only a few studies were available on the mechanical screening of woodchips. It seems that the results strongly depend on the screening method, the screening type, and the raw material. Although most of the studies conclude that screening is a promising method to increase fuel quality, its use remains somewhat sporadic. So far, only little is known about screening productivity and costs. In particular, hardly any information is available on the implementation of the screening process in woodchip supply chains. Thus, there is a strong need for studies focusing on chip production systems that consider screening alternatives. Furthermore, little is known about potential uses of the fine fraction, which contains high concentrations of nutrients. There is a great need for studies focusing on application possibilities in regard to ecological soundness and economic feasibility.

5. Conclusions

Screening offers a cost-effective method to increase the quality of woodchips. In particular, the use of star screens offers big advantages, since fine and oversize particles can be removed from the chips in one step. The results of this study indicated that it is possible to increase the quality of woodchips by screening. In particular, star screens can be used to lower ash content and to remove particles of undesirable size classes. However, the tested star screen was primarily designed to work with compost and not with woodchips. Our results showed that modifications of the screen settings are still necessary to further increase the product quality before the machine can be used effectively with fresh logging residue woodchips.

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