

# 1 **Productivity and woodchip quality of different chippers during poplar** 2 **plantation harvesting**

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5

## 6 **Abstract**

7 In this work, the productivity and work quality of different types of chipping machines used  
8 for biomass comminution produced by dedicated plantations were evaluated. Drum and disc  
9 chippers with different powers were compared with feller-chippers and grinders. Machines  
10 were tested using only one tree species (poplar) and two different feedstocks: branchwood  
11 (seven-year-old treetops and biomass produced by a vSRC) and whole-trees (materials  
12 produced by an SRC). This study showed a similar performance for all types of machines  
13 tested in terms of working rate using different feeding systems, i.e., automatic and forestry  
14 crane. However, different results were obtained for woodchip quality. The whole tree  
15 comminution was able to guarantee the best woodchips, and chippers produced better wood  
16 chips in comparison to grinders. The results obtained indicate that productivity is linked to  
17 engine power and that feedstock size can influence wood chip quality. Furthermore, feller-  
18 chippers are able to guarantee the same productivity and wood chip quality as “conventional”  
19 chippers.

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## 21 **Keywords**

22 , Chipping machines, branchwood, whole-trees, *Poplar spp.*; productivity, woodchip quality.

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## 1. Introduction

The comminution of wood is performed to homogenize different wood assortments (logs, branches, etc.) and to increase the load density [1].

Typically, woodchips are used for energy production and making chipboard panels. At present, in Italy and in Europe, large amounts of woodchips are used as biomass for energy production because there are many economic incentives for this biofuel use [2-5].

In Europe, large amounts of woodchips are produced by dedicated cultivations: short rotation coppices (SRC). Recently, the ligno-cellulosic species cultivation has increased because several farms have included SRCs in their cultural plans [6]. The main forestry species cultivated in Europe are poplar (*Populus* spp.) [7], willow (*Salix* spp.) [8], black locust (*Robinia pseudoacacia*) [9], and eucalyptus (*Eucalyptus* spp.) [10]. Forestry species can be cultivated with a high planting density (5,500–14,000 trees ha<sup>-1</sup>) and harvested every 1–4 years (very short rotation coppice - vSRC) or with a lower planting density (1,000–2,000 trees ha<sup>-1</sup>), with harvesting ranging from 5 to 7 years (short rotation coppice - SRC) [11].

Woodchips used for energy production must be of high quality (uniform size), and every chip should be of a size smaller than 60 mm to guarantee the correct automatic feeding of the power station [12]. Furthermore, woodchips should have low cortex and moisture contents because the cortex content affects ash production and the moisture content decreases the lower Calorific heating value (LCHV) [13]. If cortex and moisture content depend on timber assortment type, the chip sizes are mainly related to the chipper characteristics.

49 The chipping operation can be made during the biomass harvest or some days after tree  
50 cutting. This operation can be performed by two different groups of machines: chippers, i.e.,  
51 machines using sharp tools (knives) to cut or slice wood, and grinders, i.e., machines using  
52 blunt tools (hammers) to smash or crush wood [14]. In particular, grinders are used for  
53 contaminated wood, as their blunt tools are less sensitive to the wearing effect of  
54 contaminants but offer a rather coarse product [15]. In contrast, chippers are exclusively  
55 applied to clean wood and offer a finer and better product [12].

56 Chippers used for woodchip production for energy use can be divided by the function of their  
57 comminution devices, i.e., discs and drums [16]. All chippers offer high product quality, but  
58 disc chippers are more energy efficient than drum chippers. However, drum chippers are  
59 generally more productive [16]. Chippers can also be divided by frame type, i.e., mobile or  
60 stationary [17]. The first type are used principally for wood chipping in fields or forests,  
61 whereas the second type are assembled directly at "woodyards or terminals". Of course, the  
62 latter have a greater size and power. In SRCs, in addition to these "conventional" chippers,  
63 specific self-propelled machines exist for simultaneously harvesting and chipping the biomass  
64 produced (feller-chippers). These chippers are modified foragers equipped with a specific  
65 head that is able to cut and chip small trees [18].

66

67 Over multiple years, these different chipping machine types were tested singularly at different  
68 sites and using different feedstock types. On the basis of these tests, the goal of this work is to  
69 evaluate the productivity and work quality of different types of chipping machines used for  
70 biomass comminution produced by SRC and vSRC under the same working conditions and  
71 using the same feedstock. Drum and disc mobile chippers with different power sizes were  
72 compared with feller-chippers and grinders. Machines were tested using only one tree species  
73 (poplar spp.), but two different feedstocks were used (branchwood and whole-trees).

74

## 75 **2. Materials**

76 For this experimentation, eight different machines were chosen. In particular, three of these  
77 were powered by tractor PTOs, whereas the other five were powered by an independent  
78 engine. The tested machines required power ranging between 103 and 420 kW. In the tests,  
79 drum chippers and disc chippers were used. In addition, one grinder and three feller-chippers  
80 (self-propelled) were analysed (Table 1).

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82 To obtain the best performances, all machines were equipped with a “No stress” electronic  
83 device capable of managing the speed of the feed rolls in relation to the available power. For  
84 each machine category, an appropriate feeding system was used; self-propelled chippers were  
85 fed automatically, whereas “conventional” chippers and the grinder were fed by a forestry  
86 crane.

87 All stationary machines, in order to reduce the operator’s effect, as is well known in other  
88 forestry sectors [19], were fed using only one forestry crane driven by the same operator. The  
89 crane used in the test was a DALLA BONA AS610 fixed to a 4 WD tractor (Same  
90 ANTARES 110).

91 The poplar tree species (*Populus x euroamericana*) used in all tests is one of the main species  
92 found in Italy, and it can be considered representative of all wood types used for biomass  
93 production [20]. Because the feedstock size can influence productivity [21], in the trials, two  
94 feedstock types were used: branchwood (treetops of seven-year-old trees and biomass  
95 produced by a 2-year-old very short rotation coppice) and whole tree (materials produced by a  
96 7-year-old short rotation forest).

97 In this work, we also considered treetops because in some cases, for the economic balance of  
98 an SRC to be positive, the basal part of the trunk, up to 4-6 m, is used to produce industrial  
99 wood (OSB panel, packaging) [22].

100 Branchwood had an average diameter (measured to approximately 10 mm from the cutting  
101 section) of between 50 and 120 mm, whereas whole trees had a base diameter of between 280  
102 and 400 mm.

103 Due to the limited size of their cutting heads and to the specific cutting system type, not all  
104 chipping machines tested were able to work with two different feedstocks. Feller-chippers 1  
105 and 2 worked on the vSRC plantations (branchwood) only, whereas feller-chipper 4 worked  
106 only in the SRC (whole tree).

107 All of the wood was freshly processed, with a water mass fraction of approximately 55%.

108

109 Feedstocks were made available in large piles (approximately 100 m<sup>3</sup>) built at the field edge.

110 All machines, except feller-chippers, were stationed near the piles, and a forestry crane was  
111 used to move the wood into the feeding device. Feller-chippers worked directly in plantations  
112 (vSRC and SRC) because the feed of their cutting heads was conducted automatically in the  
113 forward speed setting. The trials were performed on a poplar vSRC, where the distance  
114 between the rows was 3.00 meters and the distance between trees was 0.50 meters (areal  
115 density of 6,700 ~~trees~~ ha<sup>-1</sup>), and a poplar SRC with the same distance between the rows but  
116 with a distance between trees of 3.00 meters (1,600 trees per hectare).

117 Each feller-chipper was tested on a rectangular area of 0.25 hectare, with dimensions of  
118 approximately 105 m in length and 24 m in width (eight rows). In particular, the rows had  
119 lengths of 95 m and headlands of 5 m.

120

121 Chips were blown into three-axle trailers with a capacity of 35 m<sup>3</sup>. Trailers were towed by  
122 farm tractors so that the whole operation was based exclusively on farming equipment.

123

### 124 **3. Methods**

125 The research was conducted in northwestern Italy, near the town of Alessadria (45° 8' 33" N;  
126 8° 28' 11" E), between January and March, 2012.

127 The sampling unit consisted of a full trailer. The experimental design aimed at testing the  
128 effect of the technical characteristics of each machine category used for woodchip production  
129 (disc chipper, drum chipper, feller-chippers, and grinder) on the productivity. Each treatment  
130 was replicated three times (Table 2).

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132 All machines worked with new knives and hammers.

133

134 Productivity was estimated through a detailed time-motion study conducted at the cycle level  
135 [23], where a full trailer load was assumed to be a cycle. Cycle times were defined and split  
136 into time elements according to the IUFRO classification [24]. The working rate of the  
137 chipping operation was expressed in terms of dry mass ( $M_g \text{ t DM h}^{-1}$ ) and density ( $m^3 h^{-1}$ ).

138 Furthermore, these parameters were also calculated as functions of chipper engine power ( $M_g$   
139  $t h^{-1}$  and  $m^3 h^{-1} \times kW$ ). The net chipping productivity of each chipper was determined  
140 considering only the productive working time.

141

142 Outputs were estimated by measuring the volume and weight of all woodchips produced  
143 during each test. The weight of each trailer was measured by a certified weighbridge with an  
144 accuracy of 10 kg (Ferrero® FL311). Before determining the trailer weight, the load was

145 levelled equal to the tipper topsides. This operation was necessary to obtain biomass density  
146 values.

147 Moisture content determination was conducted using the gravimetric method according to  
148 European Standard CENT/TS 14774-2 [25] on one sample (1 kg) per trailer, which were  
149 collected in sealed bags and weighed fresh.

150

151 The quality of wood chips was assessed on one sample (1 kg) per trailer according to  
152 European Standard EN 15149-1 [26]. Seven sieves were used to separate the following eight  
153 chip length classes: <3.15 mm (fines), 3.16-8 mm, 9-16 mm, 17-31.5 mm, 31.16-45 mm, 46-  
154 63 mm, (acceptable size), 64-100 mm, and >100 mm (oversize particles). Each fraction was  
155 then weighed according to a precision scale with an accuracy of 0.01 g (Sartorius® GP3202).

156

157 All data collected were processed using Microsoft Excel and analysed with SSPS (2013)  
158 advanced statistics software to check the statistical significance of the eventual difference  
159 between the trials. The difference between machines was determined using the Ryan-Einot-  
160 Gabriel-Welsch (REGW) test because it has higher statistical power with this data  
161 distribution.

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#### 163 **4. Results**

164 Time consumption ranged from 29 to 196 s m<sup>-3</sup> for branchwood and from 32 to 104 s m<sup>-3</sup> for  
165 whole trees (Table 2).

166 Independent of feedstock and machine type used, the net chipping time was 78% higher,  
167 whereas the supportive work time and delay showed an incidence of total work time of only  
168 2-8%. Complementary work times of the grinder were very low (approximately 8%) in  
169 comparison to the other machine types analysed (12-19%) (Table 2).

170 The statistical analysis showed all differences in the net chipping time for all machines and  
171 feedstock types tested (Table 3).  
172

173 In branchwood chipping, a higher value of productivity ( $102.67 \text{ m}^3\text{h}^{-1}$  equal to  $16.29 \text{ t h}^{-1}$ )  
174 was obtained using machine 8, whereas the lowest value was obtained using machine 1 ( $19.33$   
175  $\text{m}^3\text{h}^{-1}$  equal to  $3.06 \text{ t h}^{-1}$ ).  
176 Net productivity expressed per unit of nominal power of the machine ranged between 30 and  
177  $38 \text{ kg h}^{-1} \times \text{kW}$  (Table 4).  
178

179 In whole tree chipping, a higher working rate ( $112.67 \text{ m}^3\text{h}^{-1}$  equal to  $18.14 \text{ t h}^{-1}$  of dry matter)  
180 was obtained using machine 7, whereas a lower value ( $34.67 \text{ m}^3\text{h}^{-1}$  equal to  $6.07 \text{ t h}^{-1}$  of dry  
181 matter) was found with machine 4. Higher net productivity expressed in dry matter per unit of  
182 nominal power of the machine was obtained with machines 5 and 6 ( $60 \text{ kg h}^{-1} \times \text{kW}$ ), whereas  
183 a lower value ( $32 \text{ kg h}^{-1} \times \text{kW}$ ) was found with machine 4 (Table 4).  
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185 In a comparison of all productivity values, that obtained for whole tree chipping ( $0.053 \text{ t h}^{-1} \times$   
186  $\text{kW}$ ) was approximately 30% higher than that obtained for branchwood chipping.  
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188 Furthermore, considering that the chippers were only fed with forestry cranes, the data  
189 processing output showed an average productivity of  $0.22 \text{ m}^3\text{h}^{-1}$  or  $0.035 \text{ t of dry matter}$  per  
190  $\text{kW}$  of nominal power in branchwood chipping, and  $0.34 \text{ m}^3\text{h}^{-1}$  or  $0.058 \text{ t of dry matter}$  per  
191  $\text{kW}$  of nominal power in whole tree chipping.  
192

193 In general, chipper productivity increased in relation to the nominal power engine (Fig. 1).



194 In whole tree chipping, it is possible to obtain a higher data correlation ( $R^2 = 0.99$ ;  $y =$   
195  $0.3747x - 6.880$ ;  $P < 0.0001$ ) if the value of machine 4 (190 kw) is not considered (Fig. 1).  
196 This machine, in contrast to the other machines tested, cannot work continuously because,  
197 before performing the chipping operation, it needs to reach the tree, cut it, and successively  
198 place it in the feeding mouth. The sequence of these operations reduces its productivity (Table  
199 4).

200

201 Table 4 shows the particle size distribution of the chips produced using different machines.  
202 The acceptable size accounted for the majority of the sample weight, but the oversize particle  
203 content was substantial (14.8% of the total weight). The particle size distribution did not  
204 differ significantly between the considered feedstocks (Table 5).

205

206 Disc and drum chippers produce high-quality woodchips and show little presence of fine  
207 particles in comparison to grinders (hammers) (Table 6).

208

## 209 **5. Discussion**

210 In vSRC and SRC harvesting, independent of feeding systems adopted by chippers  
211 (automatically or with forestry crane), the supporting work time and delay are low (8% of  
212 total working time). This value is similar to those obtained in other works performed using  
213 traditional chippers [27], but it is substantially lower (four times) in comparison to the self-  
214 propelled forager modified for wood chipping tested on a poplar plantation with a diameter of  
215 270 mm [28]. This difference could be attributed to the smaller tree sizes and the optimal  
216 conditions (large square and large head field) that machines have worked during the trials.  
217 Overall, it is very important to highlight that the working time can also be linked to the  
218 operator's training and skill level [29].

219

220 Productivity is influenced particularly by rotation length of the SRC harvesting because a  
221 different plantation edge can lead to different feedstock types. In fact, it is lower when the  
222 wood assortment processed is characterized by a small size (branchwood - vSRC). This effect  
223 may be attributed to low feedstock density and the greater difficulty of its operation. This  
224 feedstock can also cause some problems in feeding operations, where the branches can  
225 become stuck in the feeding mouth of the chippers. These operative problems were also  
226 shown in other studies [12, 30].

227

228 Furthermore, this study has highlighted that cutting operations performed simultaneously with  
229 the chipping operations (feller-chippers) do not considerably reduce chipping operation  
230 productivity or influence woodchip quality. The results also indicate the strong performance  
231 of feller-chippers, which in previous tests, have shown economic advantages [31] and less soil  
232 compaction [32] compared to other machines used in tree cutting and wood comminution.  
233 Nevertheless, machine 4 (i.e., a feller-chipper that worked only in the SRC – a plantation with  
234 a medium-length rotation) showed a low working rate because its working process was not  
235 continuous due to the difficulty of cutting trees with large diameters (up to 400 mm). In fact,  
236 as reported by Hauk et al. [33], when the SRC rotation length is long (7 years), manual  
237 harvesting becomes economically competitive.

238

239 In this study, it is noted that independent of the machine type used (self-propelled chippers,  
240 feller-chippers or grinders) in biomass comminution, the productivity was strictly related to  
241 the nominal engine power. These results are comparable with those found in previous works  
242 [12, 17]. The difference of singular values could be linked to different forestry cranes used  
243 and differences in operator skills.

244

245 The particle size distributions obtained in this experiment are very similar to those obtained in  
246 other experiments conducted in similar conditions [34-38].

247 The woodchips are of high quality for all of the chippers tested (acceptable size > 80%)  
248 except for the grinder (acceptable size < 67%). This trend is similar to that found in other  
249 works where the biomass was processed with grinders [15]. Independent of the machine type  
250 considered, in this work, feedstock biomass sizes influenced woodchip quality. The best  
251 biofuels were obtained with the whole tree chipping (acceptable size > 88%). The production  
252 of many fine particles using branchwood or materials with small diameters was also  
253 confirmed by Spinelli et al. [39]. In contrast to Nati et al. [40], in this study, disc and drum  
254 chippers show no significant difference in woodchip quality (Table 5). This result could be  
255 related to the single forestry species (poplar) processed in this study.

256

257 Considering the importance of forestry species [34-35, 41] and the effect of wear knives on  
258 the machine productivity and woodchip quality [42], it could be useful to improve these  
259 results with others studies conducted with the same machines but using different forestry  
260 species and wear knives.

261

## 262 **6. Conclusions**

263 This study showed similar performances for all type of machines tested in terms of specific  
264 working rate (working rate expressed by unit of nominal power). No difference in  
265 productivity was obtained using different feeding systems (automatic and with forestry crane)  
266 and commination systems (disc, drum or hammers). However, different results were obtained  
267 in woodchip quality. In fact, in order to obtain high-quality wood chips, large size feedstock  
268 (whole tree) and chippers (drum or disc) were required.

269 This information is very important because it is useful for consideration during biomass  
270 plantation planning and management.  
271 Finally, the data obtained in this experiment highlight that in the SRC, it is better to use feller-  
272 chippers. In fact, these machines, in addition to ensuring the same performance of  
273 “conventional” chippers in terms of productivity and wood chip quality (results obtained in  
274 this work), are able to reduce soil compaction and hourly costs (results obtained in other  
275 studies [30-31]).

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