Energy consumption and CO2 analysis of different types of chippers used in wood biomass plantations

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Abstract

Woodchip is preferred to all biomass forms because it shows standardised sizes and offers additional benefits in terms of load density. In Europe, a large amount of woodchip is produced by dedicated cultivations: very Short Rotation Coppice (vSRC) and Short Rotation Coppice (SRC). The chipping operation can be done during the biomass harvest or some months after tree cutting. This operation can be performed by different machines: disc chippers, drum chippers, feller-chippers and grinders.

The goal of this work was to determine the energy and the CO_2 emission of different types of chippers used in biomass comminution produced by poplar vSRC and SRC. All machines were tested with two different feedstocks: branchwood (treetops and biomass produced by vSRC) and whole-trees (biomass produced by SRC).

Fuel consumption ranged between 14.36 and 59.52 l h^{-1} and energy consumption varied from 0.92 to 0.62 MJ $MgDM^{-1}$, respectively, for branchwood and whole-trees feedstock type. In addition, an average value of 16.40 $kgCO_2eq$ $MgDM^{-1}$ in branchwood chipping and an average value of 10.80 $kgCO_2eq$ $MgDM^{-1}$ were obtained in CO_2 assessment.

This experiment indicated that self-propelled feller-chippers were significantly more convenient than “conventional chippers” in biomass comminution produced by dedicated plantations.

Keywords

Chippers, feller-chippers, grinders, fuel consumption, energy cost, CO_2 emission

1. Introduction

Energy produced by renewable sources is considered a valid solution for reducing environmental pollution caused by the use of fossil fuels [1-2]. In fact, recently, the European Union has provided incentives for renewable energy production [3]. Among all renewable energy sources, biomass is the one that has the greatest possibility for fossil fuel substitution [4], especially woodchip [5], which is preferred over all other biomass forms because it shows standardised sizes and offers additional benefits in terms of load density [6].

The chipping operation can be done during the biomass harvest [7] or some months after tree cutting [8]. This operation can be performed by two different groups of machines: chippers—machines using sharp tools (knives) to cut or slice wood; and grinders—machines using blunt tools (hammers) to smash or crush wood [9].

In particular, grinders are used when dealing with contaminated wood, as their blunt tools are less sensitive to the wearing effect of contaminants [10], but offer a biofuel of low quality level, unsuitable for use in some plants [11]. In contrast, chippers are exclusively applied to clean wood and offer a finer and better product [12]. For wood comminution, mobile and stationary chippers are used, but the former, despite their inferior performance, are more diffused in forestry yards [13].

In Europe, a large amount of woodchip is produced by dedicated cultivations: Short Rotation Coppice (SRC). In recent years, the ligno-cellulosic species cultivation has increased because several farms have inserted SRC in their cultural plans [14]. The main forestry species cultivated in Europe are poplar (*Populus* spp.) [15], willow (*Salix* spp.) [16], black locust (*Robinia pseudoacacia L.*) [17] and eucalyptus (*Eucalyptus* spp.) [18]. Forestry species can be cultivated with a high planting density (5,500–14,000 plants ha^{-1}) and harvested every 1 to 4 years (very Short Rotation Coppice—vSRC) or with a lower planting density (1,000–2,000 plants ha^{-1}) and harvested ranging from 5 to 7 years (Short Rotation Coppice-SRC) [19].

Until now many works have focused on various aspects of vSRC or SRC: genotype selection [20], cycle duration [21], biomass production [22], planting techniques [23], weed control and fertiliser effect [24], pesticides application [25], irrigation effect [26], etc. Among all SRC cultural operations, biomass harvesting is considered crucial for a farmer to estimate the economic sustainability of the crop in advance [27]. In fact, recently, the biomass harvesting operation has been studied from different points of view: harvesting techniques [28], economic and energetic costs [29], and wood chip quality [30]. Since biomass harvesting-especially woodchip production [29]—requires approximately 25% of the total SRC energy input [31], it is very important to make a correct choice of the machine used to reduce total energy consumption.

In recent years, some works have focused on the evaluation of chipper performance but unfortunately, all of these have considered only a single machine or various machines but not under the same work conditions (these experimentations are different in terms of feedstock characteristics, materials and methods used) [7, 13, 27]. They do not give sufficient information to compare the performance of different types of chipper machines used in SRC plantations.

In order to overcome this deficiency, a specific study was performed in which the performances of different types of machines used in wood chip production were assessed under the same working conditions. On this basis, the goal of this work was to determine the energy and the CO_2 emission of different types of chippers, usually used in biomass comminution produced by poplar vSRC and SRC, in the same area and using the same feedstocks. In particular, in this study, disc and drum chippers, feller-chippers and grinders were tested with two different feedstocks: branchwood (treetops and biomass produced by vSRC) and whole-tree (biomass produced by SRC).

2. Materials

For this study, eight different machines were chosen. In particular, three of these were powered by the tractor's PTO, while five by an independent engine. All machines required power between 103 and 420 kW. In the tests, drum chippers and disc chippers were compared to one grinder and three feller-chippers (self-propelled) (Table 1).

Table 1 – Technical characteristics of the chippers and grinder tested

Machine (n°)	Machine (type)	Powered system	Power (kW)	Chipper (type)	Knives (number)	Mouth feeding size (mm)	Feeding system
1	Feller-chipper	Power Take Off	103	disc	3	250 x 600	automatically
2	Chipper	Power Take Off	130	disc	3	700 x 600	with crane
3	Chipper	Indep. engine	170	drum	4	650 x 900	with crane
4	Feller-chipper	Power Take Off	190	disc	2	700 x 600	automatically
5	Chipper	Indep. engine	200	drum	4	350 x 600	with crane
6	Chipper	Indep. engine	310	drum	2	650 x 900	with crane
7	Grinder	Indep. engine	320	hammer	38	700 x 1500	with crane
8	Feller-chipper	Indep. engine	420	drum	4	300 x 600	automatically

For each machine category an appropriate feeding system was used; self-propelled chippers were fed automatically, while "conventional" chippers and the grinder were fed by forestry cranes. All stationary machines, in order to reduce the effect of the operator's training and skill level, already well known in other forestry sectors [32], were fed using only one forestry crane driven by the same operator. The crane used in the test was a DALLA BONA AS610 fixed to a 4 WD tractor (Same ANTARES 110).

All machines were tested with only poplar tree species (*Populus x euroamericana*). Hybrid poplar is the main species used for the afforestation of north Italian farmland, and it can be considered representative of all types of wood used for biomass production [20]. Since the feedstock size can cause an effect on machine performance [33], in the trials, two feedstock types were used: branchwood (seven year-old treetops and biomass produced by a two year-old very Short Rotation Coppice), and whole tree (materials produced by Short Rotation Forestry of seven year -olds).

In this work, treetops were also considered because in some cases, in order to become positive, the economic balance of SRC, the basal part of the trunk, up to 4–6 m, is used to produce industrial wood (OSB panel, packaging) [34].

Branchwood had an average diameter (measured to about 10 mm from cutting section) of between 50 and 120 mm, while the whole tree had a base diameter between 280 and 400 mm. Due to the limited size of their cutting heads and to the specific cutting system type, not all chipping machines tested were able to work with the two different feedstocks. Feller-chippers 1 and 8 worked on vSRC plantations (branchwood) only, while feller-chipper 4 worked only in SRC (whole tree).

All wood was freshly processed, with a moisture content of about 55%.

Feedstock was made available in large piles (approximately 100 m^3) built at the field edge. All machines, except feller-chippers, were stationed near the piles and the forestry crane was used to move the wood into their feeding device. Feller-chippers worked directly into the plantation (vSRC and SRC) because the feed of their cutting heads has carried out automatically during forward speed. The trials were performed on a poplar vSRC, where the distance between the rows was of 3.00 metres and the distance between plants was of 0.50 metres (density of 6,700 plants per hectare), and a poplar SRC with same distance between the rows but with a distance between plants of 3.00 metres (1,600 plants per hectare).

Each feller-chipper was tested on a rectangular area of 0.25 hectares with sizes of approximately 105 metres in length and 24 metres in width (8 rows). In particular, the rows showed a length of 95 metres and a headland of 5 metres.

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

3. Methods

The research was conducted in northwestern Italy, near the town of Alessandria, between January and March 2012.

The sampling unit consisted of a full trailer. The experimental design aimed at testing the effect of machine categories used for woodchip production (disc chipper, drum chipper, feller-chippers, and grinder) on productivity, energy consumption and CO_2 emission.

All machines worked with new knives and hammers.

3.1. Productivity

Productivity was estimated through a detailed time-motion study conducted at the cycle level [35], where a full trailer load (35 m^3) was assumed as a cycle. Cycle times were defined and split into time elements, following the International Union of Forest Research Organisations (IUFRO) classification [36]. Productivity of the chipping operation was expressed in terms of mass (Mg DM h^{-1}) and density ($m^3 h^{-1}$). Furthermore, these parameters were also calculated as a function of chipper engine power (Mg DM h^{-1} and $m^3 h^{-1}$ x kW). Net chipping productivity for each chipper was determined considering only productive working time (time which the woodchip produced).

Outputs were estimated by measuring the volume and weight of all woodchips produced during each test. The weight of each trailer was measured by a certified weighbridge with an accuracy of 10 kg (Ferrero® FL311). Before determining the trailer weight, the load was leveled equal to tipper topsides. This operation was necessary to obtain density values of biomass. Moisture content determination was conducted with the gravimetric method according to European Standard CENT/TS 14774 [37], on one sample (1 kg) per trailer, collected in sealed bags and weighed fresh.

3.2. Energy Consumption

Energy consumption was calculated considering direct energy consumption (fuel and lubricant consumption) and indirect energy consumption (energy for the machines manufacturing) [38]. Inputs were transformed into energy unit measures adopting coefficients: machine 92.0 MJ kg^{-1} and equipment 69.0 MJ kg^{-1} [39]. Direct energy input was calculated by multiplying the fuel and lubricant consumption by the respective energy contents: 37.0 MJ l^{-1} for fuel [40] and 83.7 MJ kg^{-1} for lubricant [39], and then inflating this value by 1.2 MJ kg^{-1} as additional fossil energy used in their production, transportation and distribution [41].

In this experimentation, a life of 12,000 hours and an annual utilisation of at least 500 hours were assumed for tractors (with the tractor also being used for other operations) and a life of 8000 hours and an average annual utilisation of 350 hours was considered for chippers and grinder [29]. Energy spent for maintenance and repair was considered 55% of the energy needed for machine manufacturing [42].

Fuel consumption for the whole chipping operation was determined by a "topping-off system". With this method, fuel consumption was determined by refilling the machine tank after each trailer (35 m^3) was produced. The tank was refilled using a 2-litre glass pipe with 0.02-litre graduations, corresponding to the accuracy of measurements [43]. The lubricant consumption was determined as a function of fuel consumption in a measure of 2% [44].

3.3. Environmental assessment

The environmental impact of the chipping operations was performed considering CO_2 emitted by fuel combustion during the work and CO_2 emitted during machinery production. On the basis of research published, an amount of 3.76 kg of CO_2 per litre of diesel fuel [45-46] and an average 2.94 kg of CO_2 for each kg of lubricant [47] emitted in the atmosphere were considered. Moreover, the environmental impact required for maintenance was calculated considering an emission factor of 0.159 kg CO2 per MJ of energy content in the machines [29].

The collected data were processed with Microsoft Excel software and analysed with SPSS 21 (2014) advanced statistics software to determine the statistical significance of the differences between the treatments using ANOVA. A statistical GLM approach considering the machinery's nominal power effect on the different parameters analysed in this experimentation was not carried out because the machine characteristics were implicitly inserted in the information related to the unit of nominal power.

4. Results

4.1. Productivity

In branchwood chipping, the higher value of productivity (102.67 m^3h^{-1} equal to 16.29 Mg DM h^{-1}) was obtained using machine 8, whereas the lowest value was obtained using machine 1 (19.33 m^3h^{-1} equal to 3.06 Mg DM h^{-1}). Net productivity expressed for each nominal power unit of the machine ranged between 30 and 38 kg DM h^{-1} x kW-values always obtained by machines 1 and 8 (Table 2). However, in whole tree chipping, the higher value of the working rate (112.67 m^3h^{-1} equal to 18.14 Mg DM h^{-1}) was obtained using machine 7, whereas the lower values (34.67 m^3h^{-1} equal to 6.07 Mg DM h^{-1}) with machine 4. A higher value of net productivity expressed for each nominal power unit of the machine was obtained with machines 5 and 6 (60 kg DM h^{-1} x kW), whereas a lower value (32 kg DM h^{-1} x kW) with machine 4 (Table 2). The lower value obtained from machine 4 is related to its discontinuous work due to manoeuvres required by its positioning near the trees.

The productivity obtained in whole tree chipping (0.053 Mg DM h^{-1} x kW) was about 30% higher than that obtained in branchwood comminution (Table 2).

During data interpretation, if the values of machine 4 are not considered with regard to its peculiarities, it is possible to assert that productivity is affected only by feedstock size and not by different comminution systems, powered systems and feeding systems (Table 2).

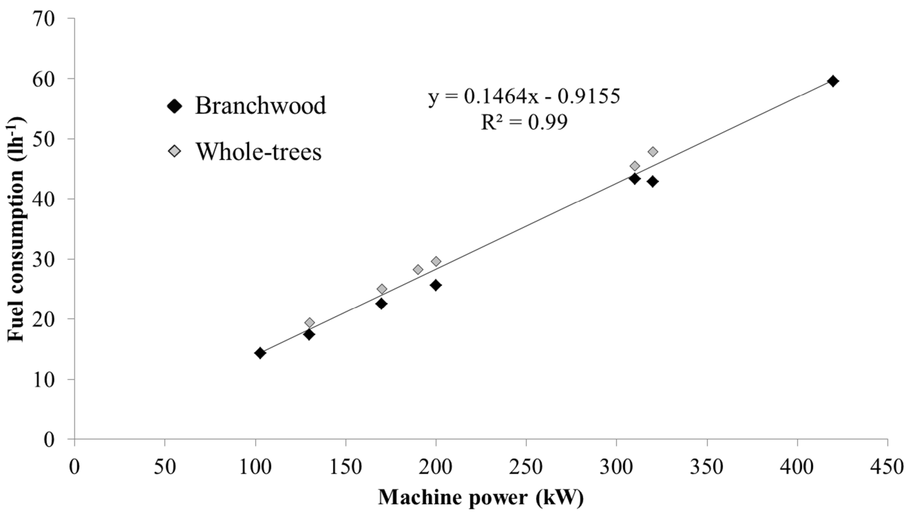
Table 2 – Productivity and statistical analysis of the all machines for each feedstock tested

Feedstock	Machine	Productivity				Specific productivity (*)			
		(m^3 h^{-1})		(Mg DM h^{-1})		(m^3 h^{-1} kW-1)		(Mg DM h^{-1} kW-1)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Branchwood	1	19.33	0.58	3.06	0.09	0.19a	0.005	0.030a	0.0007
	2	27.67	1.53	4.36	0.24	0.21a	0.005	0.034a	0.0008
	3	37.67	0.58	5.93	0.09	0.22a	0.003	0.035a	0.0005
	5	39.33	1.53	6.88	0.27	0.20a	0.005	0.034a	0.0009
	6	70.33	2.08	11.47	0.06	0.23a	0.003	0.037a	0.0002
	7	75.00	1.00	10.77	0.21	0.23a	0.002	0.034a	0.0006
	8	102.67	4.04	16.29	0.64	0.24a	0.006	0.038a	0.0010
Whole-trees	2	43.00	2.00	7.22	0.34	0.33b	0.009	0.056b	0.0015
	3	55.33	4.16	9.49	0.71	0.33b	0.024	0.056b	0.0041
	4	34.67	1.53	6.07	0.27	0.18a	0.004	0.032a	0.0006
	5	68.00	4.00	11.90	0.70	0.34b	0.012	0.060b	0.0020
	6	110.00	4.36	18.48	0.73	0.35b	0.005	0.060b	0.0008
	7	112.67	0.58	18.14	0.09	0.35b	0.001	0.057b	0.0001

Notes: (*) Values refer to a nominal power of the machine; different letters (a, b,) indicate significant differences between machines for $\alpha = 0.05$

4.2. Fuel consumption

Fuel consumption ranged between 14.36 and 59.52 l h^{-1} as a function of the nominal power of machines and the feedstock type (Table 3). Hourly fuel consumption increased in accordance with the power engine with a linear trend independently of the machine and feedstock types (Fig. 1).



Notes: values reported in this figure are a mean of three replicates

Figure 1 – Fuel consumption versus nominal machine power

Specific fuel analysis showed different values as a function of the parameter considered. Referring fuel consumption to biomass produced, independently of whether the latter is expressed in terms of weight or volume, higher values (3.90 l $MgDM^{-1}$ or 0.63 l m^{-3}) were obtained in branchwood comminution, while lower values were observed in whole tree chipping (2.60 l $MgDM^{-1}$ or 0.44 l m^{-3}). Feller-chippers powered by tractors (machines 1 and 4) showed higher values (4.67 l $MgDM^{-1}$ or 0.79 l m^{-3}) when compared to other machines independently of the feedstock considered. That statistical difference was not found when referring the specific fuel consumption to engine nominal power. In fact, for each feedstock tested, all machines showed similar values. In particular, average values of 113 and 123 g kW h^{-1} were observed in branchwood and whole tree chipping respectively (Table 3).

Table 3 – Fuel consumption during branchwood and whole-tree chipping

Feedstock	Machine	Power (kW)	Fuel measured (lh^{-1})		Specific fuel consumption		
			Mean	SD	$l\ Mg\ DM^{-1}$	$l\ m^{-3}$	$g^{(*)}\ kW\ h^{-1}$
Branchwood	1	103	14.36	0.61	4.69c	0.74c	116b
	2	130	17.45	0.54	4.00b	0.63b	112b
	3	170	22.52	0.89	3.80b	0.60b	110b
	5	200	25.68	1.26	3.73b	0.65b	107ab
	6	310	43.32	0.84	3.78b	0.62b	116b
	7	320	42.86	0.76	3.98b	0.57b	111b
	8	420	59,52	0.98	3.65b	0.58b	118b
Whole-trees	2	130	19.40	1.14	2.69a	0.45a	124c
	3	170	25.05	0.78	2.64a	0.45a	123c
	4	190	28.27	0.86	4.66c	0.82c	124c
	5	200	29.62	2.15	2.49a	0.44a	123c
	6	310	45.50	1.36	2.46a	0.41a	122c
	7	320	47.86	0.68	2.64a	0.42a	124c

Notes: (*) Value calculated considering a diesel fuel density of 0.832 g cm^{-3}; different letters (a, b, etc.) indicate significant
differences between treatments for $\alpha = 0.05$

4.3. Energy evaluation

Energy consumption in chipping operations resulted independently of the nominal power engine and in inverse relation to feedstock size comminuted. In fact, the higher value (0.92 MJ $MgDM^{-1}$) and the lower value (0.62 MJ $MgDM^{-1}$) were obtained from branchwood and from whole-tree chipping, respectively. The highest values (1.19 MJ $MgDM^{-1}$), also for this parameter, were observed in chippers powered by tractors (Table 4). In addition, this evaluation pointed out that chipping operations required an average energy consumption of 6.50 MJ for each kW of chipper nominal power independently of machine type, feeding system and feedstock size. All machines showed an incidence of direct energy consumption on total energy consumption between 80 and 90%; no statistically significant difference was observed for different feedstock considered (Table 4).

Table 4 – Energy consumption in chipping operation

Feedstock	Machine	Energy consumption: Direct (MJ h-1)	Energy consumption: Indirect (MJ h-1)	Energy consumption: Total (MJ h-1)	Specific energy consumption: Energy per nominal power (MJ kW-1)	Specific energy consumption: Incidence of direct on total (%)	Specific energy consumption: Energy per biomass produced (MJ MgDM-1)
Branchwood	1	555.4	137.4	692.8	6.71a	81.0	1.20c
	2	674.9	162.2	837.1	6.44a	80.6	0.98b
	3	870.9	108.7	979.7	6.13a	88.9	0.88b
	5	993.1	251.3	1244.5	6.21a	79.8	0.96b
	6	1675.4	213.9	1889.3	6.11a	88.7	0.91b
	7	1657.6	303.0	1960.6	6.13a	84.5	0.87b
	8	2301.9	352.9	2654.8	6.32a	86.7	0.90b
Whole-trees	2	750.3	162.2	912.5	6.90ab	82.2	0.67a
	3	968.8	108.7	1077.5	6.34a	89.0	0.61a
	4	1093.3	251.3	1344.6	7.01ab	81.3	1.18c
	5	1145.5	213.9	1359.4	6.80a	84.3	0.61a
	6	1759.7	267.4	2027.0	6.54a	86.8	0.59a
	7	1850.9	303.0	2154.0	6.73a	85.9	0.62a

Notes: different letters (a, b, etc.) indicate significant differences between treatments for $\alpha = 0.05$

4.4. Environmental assessment

Data processing highlighted an average value of 16.40 kgCO_2eq MgDM^{-1} (2.61 kgCO_2 m^{-3}) in branchwood chipping and an average value of 10.80 kgCO_2eq MgDM^{-1} (1.82 kgCO_2 m^{-3}) in whole-tree chipping. Also, in this evaluation the worst results were obtained by the chippers powered by the tractor. In fact, independently of feedstock considered, an amount of approximately 20.30 kgCO_2eq MgDM^{-1} (3.38 kgCO_2 m^{-3}) was obtained by a chipper powered by tractors (Table 5). No statistical differences were found between machines equipped with different comminution system and feeding system used.

Table 5 – CO_2 emission during branchwood and whole-tree chipping

Feedstock	Machine	CO_2 eq emission	
		$kgCO_2eq\ MgDM^{-1}$	$kgCO_2\ m^{-3}$
Branchwood	1	20.45c	3.24c
	2	17.38b	2.74b
	3	17.26b	2.72b
	5	16.31b	2.85b
	6	15.48b	2.52b
	7	16.78b	2.41b
	8	15.18b	2.41b
Whole-trees	2	11.53a	1.94a
	3	10.73a	1.84a
	4	20.12c	3.52c
	5	10.52a	1.84a
	6	10.22a	1.72a
	7	11.02a	1.77a

Notes: different letters (a, b, etc.) indicate significant differences between treatments for $\alpha = 0.05$

5. Discussion

During biomass plantation harvesting, independent of feeding system types used in chipping operations (automatically or with forestry crane), the supporting work time and delay (unproductive time) were low (8% of total working time). This value is similar to that obtained in other work performed using traditional chippers [48], but is much lower (four times) in comparison to a self-propelled forager modified for wood chipping tested on a poplar plantation of 270 mm diameter [49]. This difference could be attributed to the lower tree sizes and to the optimal conditions (large square and big head field) in which the machines worked during the trials. Overall it is very important to highlight that working time can also be linked to the operator’s training and skill level [50].

Productivity is influenced particularly by the rotation length of the SRC harvested because a different plantation edge causes a different feedstock type (Table 6). It is lower when the wood assortment processed is characterised by a small size (branchwood or vSRC). This effect may be attributed to low feedstock density and to greater difficulty in its handling. This wood assortment type can also cause some problems in feeding operations, where the branches can get stuck in the feeding mouth of chippers. These operative problems were also shown in other studies [51-52].

Independent of the type of machine considered (feller-chipper, chipper or grinder), the working rate results are similar for all machines with similar nominal engine power; different values are obtained only with different feedstock. This is confirmed in the database compiled by Spinelli and Magagnotti [13] and in the study conducted by Spinelli et al [51]. The minor differences between the values could be attributed to different feed systems (automatic or with crane) and operator skill. In addition, no significant difference was found by adopting a different comminution system (disc, drum, hammer).

In absolute terms, fuel consumption obtained in this work was in line with the values reported by Nati et al. [53] (0.8 to 1.6 l t^{-1}) and by Spinelli et al. [51] (1.7-1.8 l t^{-1} for poplar). Moreover, these results are similar to those assumed for a life cycle assessment of fuel wood chip production from willow [54] and eucalyptus [55] biomass plantations.

Furthermore, this study highlights that in biomass comminution, independently of the machine type used (self-propelled chipper, feller-chipper or grinder) and feedstock size (branchwood or whole-trees), fuel consumption is strictly related to the engine’s nominal power of the chipping machine used. A similar trend was also found by Spinelli and Hartsough [56] during a survey of chipping operations performed with conventional chippers. Since fuel consumption is proportional to engine load, these results could be linked to max rotation speed of the engine used to power the machine [57]. In fact, at high rotation speed, eventual change of load due to resistance forces of different feedstock size is better endured by the engine [58]. In addition, when the chippers are equipped with a no-stress electronic device (a device to control the forward speed of the feeding material in function of engine speed), in order to obtain a high woodchip quality, the engine works with a constant speed, and for this reason, with a fairly constant load for all feedstock size variations as well [51]. Also for this parameter, statistical analysis showed no significant difference between machines equipped with different comminution system and feeding system. Differences were observed only when machines powered by PTO of the tractor were considered.

Referring the energy consumption in biomass comminution to nominal power of machines used, a similar value was obtained for all machines tested (6.50 MJ for each kW) independently of machine type, feeding system and feedstock size. However, relating energy consumption to woodchips produced, the highest mean value (0.92 MJ $MgDM^{-1}$) was observed during the comminution of feedstock of small size (branchwood), and the lowest mean value (0.62 MJ $MgDM^{-1}$) during whole-tree chipping. Also for this parameter, these results can be attributed to the constant engine load guaranteed by a no-stress device and to different productivity that is obtainable using different feedstocks. The highest absolute value (1.18 MJ $MgDM^{-1}$) observed in chipper 4 powered by PTO of the tractor could be related to a lower working rate and lower efficiency of the power transmission system. In fact, when using the PTO and a hydraulic power transmission system, part of the power provided by the engine is absorbed by the cardan shaft used to couple the chippers to tractors and the pump used to maintain the oil under pressure [59].

In general terms, the energy required by a chipping operation is very low (0.6–1.2 %) when compared with the energy value of the woodchip produced (1880 MJ $MgDM^{-1}$). These results are comparable to those found by other researchers in similar plantations [60-61]. In addition, this study indicates an average incidence of about 85% of the direct energy (fuel and lubricant consumption) on total energy required. These results are similar to those calculated for woodchip transportation [62] and biomass harvesting [29].

Regarding CO_2 emission during biomass chipping, data processing highlights a different value in function of feedstock size. Higher results were obtained in whole-tree comminution (16.40 kg CO_2eq $MgDM^{-1}$) compared to 10.80 kgCO_2eq $MgDM^{-1}$ emitted during branchwood chipping. This trend can be caused by different chippers' productivity. In fact, whole-trees have highlighted higher wood chip production in the unit time. These values are in line with those found during a life cycle assessment of chip production from eucalypt forestry residues [55] and poplar SRC [60,63].

Also in this case, the chippers powered by a tractor showed the worst results independently of feedstock physical characteristics (20.30 $kgCO_2eq\ MgDM^{-1}$). This aspect is very important and it should not be underestimated because the CO_2 emission, as well as being detrimental to the environment, is also harmful for the operators [64].

Finally, the study highlighted that the cutting operation performed in simultaneity with the chipping operation (feller-chippers) does not considerably reduce chipping operation productivity and does not influence fuel and energy consumption. These results again increase the high performance of self-propelled feller-chippers that in previous tests have shown advantages in economy [27] and soil compaction [28] when compared to "conventional" machines used in biomass harvesting and chipping. Nevertheless, machine 4 (feller-chipper that worked only in SRC–plantation with a medium-length rotation) showed a low working rate because its working process was not continuous due to difficulty in cutting trees with large diameters (up to 400 mm). In fact, under these conditions, manual cutting and harvesting can be economically competitive compared to mechanical systems [65].

6. Conclusions

In conclusion, the data processed showed that all parameters analysed in this study (productivity, energy consumption, and CO_2 emitted) are mainly affected by feedstock size and powering system of the machines used. Different comminution systems (disc, drum, and hammers) and feeding systems (automatic and with forestry cranes) do not significantly influence the values.

In addition, the study highlighted a significant advantage in the use of self-propelled feller–chippers because these machines, although performing two operations simultaneously (cutting trees and chipping wood) show a similar performance to "conventional chippers".

Nevertheless, feller-chippers powered by PTO of tractors do not seem to be a good solution because they have shown the worst results in terms of productivity, energy consumption, and CO2 emitted.

On the base of the results obtained in this study, in order to reduce the environmental impact of the chipping operations, especially GHG emission, manufacturers should focus on machines with an independent engine, while farmers should plan their crops with long harvest cycles (seven years).

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