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Medium Rotation *Eucalyptus* Plant: A Comparison of Storage Systems

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Abstract: *Eucalyptus* spp. are among the most suitable species for biomass production, even for the firewood derived from medium-rotation coppice (MRC). The general problem of wood is that it cannot be utilized immediately because of the high moisture content, which in the combustion process would reduce remarkably the yield of energy. In this context, outdoor storage of whole stems without branches (WS), outdoor storage of whole stems with branches (WSB), open shed storage of firewood logs in mesh bags (OSF), and outdoor firewood logs in mesh bags (ODF) of *Eucalyptus* spp woody biomass were compared in term of moisture and dry matter loss to evaluate the most convenient form of storing biomass deriving from a medium-rotation coppice. During the storage period, ODF showed higher moisture values than OSF, WSB, and WS, underlining that moisture reduction is related to local climatic conditions, pile size and permeability (compaction). However, at the end of the storage period, the four options reached a similar moisture to the commercial one of fuel wood (around 15%). WSB showed the highest loss of dry matter (18%), which can be ascribed to the drying and falling process of the leaves. In conclusion, the qualitative and quantitative characteristics of the biomass were similar after the different storage systems, producing firewood suitable for new market opportunities.

Keywords: *Eucalyptus*; tree whole stem; firewood logs; storage system; moisture content; dry matter loss

1. Introduction

Renewable biomasses play a crucial role in mitigating climate change as a substitute for fossil fuels [1,2]. Plantations on agricultural land give an opportunity for producing biomass sustainably and improving farm income [3]. Fast-growing trees are one of the most promising alternatives for the production of biomass when planted in short-rotation coppice [4,5]. However, this system can be divided into very-short-, short- and medium-rotation systems depending on density of plantation and cycle length [6]. In recent years, there has been growing interest in extending the rotation age to a five-year cycle (medium-rotation coppice). This is due to an actual advantage of medium-rotation coppice (MRC) in terms of yield maximization (high quantity of biomass at low plant density), a great improvement of the product quality (reduced bark/fiber ratio) and less dependence on adverse seasons [7,8]. *Eucalyptus* spp. are among the most suitable species for biomass production, because of their rapid adaptability to different climatic conditions, even Mediterranean ones, and easy use in plant breeding programs [9]. Worldwide, commercial plantations of these species, 20 million ha, are the main source of lignocellulosic biomass for cellulose pulp and the production of energy [10]. Plantations are mainly located in temperate areas, but they can be found in climates with a dry season, such as that of the Italian peninsula. In the Mediterranean environment, *Eucalyptus* spp. plantations are largely cultivated in Spain and Portugal, with an amount of cropped area above 600,000 ha [11]. The cultivated surface in Italy is much lower, corresponding to about 70,000 ha; among these, the cultivation for energy productions is limited to 20,000 ha and is mainly concentrated in Sicily and Sardinia [12].

In general, the surface of energy plantations in Italy is not enough to cover the demand for biomass for energy production, and, in the last ten years, Italy has become one of the world's largest importers of woody biomass for energy use [11].

However, despite a limited distribution, there is a growing interest in cultivating *Eucalyptus* in Italy, especially in MRC plantations, which allow obtaining trunks suitable for firewood production, a product having higher economic value relative to wood chips [13].

The biomass of *Eucalyptus* presents good quality characteristics for being utilized as firewood, with similar characteristics to classical firewood species (for example, oak and beech) (Table 1), unlike other tree species identifiable in MRC plantations, such as poplar, where the wood burns very fast without producing embers [13].

Table 1. Fuel quality parameters of different species.

Species.	Unit	Heating Value	References
Birch	MJ Kg^{-1}	18	[14]
Spruce	MJ Kg^{-1}	18.6	[14]
Beech	MJ Kg^{-1}	19.8	[15]
Maple	MJ Kg^{-1}	18.5	[14]
Oak	MJ Kg^{-1}	19.17	[16]
Poplar	MJ Kg^{-1}	18.5	[17]
Willow	MJ Kg^{-1}	18.4	[17]
Eucalipts	MJ Kg^{-1}	19.44	[18]

However, beside the harvesting phase, the general problem of wood is that it cannot be utilized immediately because of the high moisture content, which in the combustion process would reduce remarkably the yield of energy. This is because part of the energy is spent to evaporate the water present in the biomass to permit combustion [19]. However, using boilers with flue gas condensation reduce energy loss even for moist biomass [20].

The moisture content is therefore an important property when considering the energetic potential of any biomass, because it has the greatest influence on the energetic variation of the material [21,22]. Hence, between harvesting and utilization, the wood must be stored to reduce the moisture content and optimize the energy yield when it is burned. On the other hand, storage is a factor that can also negatively affect the wood characteristics. Key mechanisms responsible for the major changes in woody biomass during storage are: (i) living cell respiration, (ii) biological degradation, and (iii) thermo-chemical oxidative reactions. All three mechanisms involve mass-to-energy conversion and dry matter losses. Living cell respiration is a short-term effect that lasts only several weeks, while starch and sugar are readily available and adequate temperature and oxygen levels are present. Biological degradation is caused by a large variety of organisms, from bacteria to wood-degrading fungi, which can also produce toxic compounds [23] and function best under specific moisture, temperature and oxygen conditions. Finally, thermo-chemical oxidative reactions can contribute to excessive dry matter loss once elevated temperatures have been attained in biomass as a consequence of the first two mechanisms [24].

All these processes can alter the biomass characteristics and determine dry matter loss. For this reason, it is important to identify suitable storage forms and solutions to facilitate the drying process of wood, limiting its degradation. Normally, the biomass harvested from MRC of *Eucalyptus* is chipped and then stored until utilization. The comminution of the biomass after harvesting requires large areas for the storage of biomass in piles, and is subjected to degradation phenomena. On the contrary, it is possible to harvest the biomass and to store it as whole stem on the field edge; at the end of the storage time, it is still possible to chip the biomass or to produce firewood depending on market demand. In this context, the objective of the study was to measure the qualitative and the quantitative parameters (humidity after storage and losses of dry matter) of whole stem and firewood logs storage, to evaluate the most convenient form of storing biomass deriving from a medium-rotation *Eucalyptus* (MRC) plant as alternative to biomass comminution. At present, only a few experiences of *Eucalyptus* storage as whole stem logs have been recorded in Europe and no experience of firewood is recorded, even if recent studies [25] have reported the availability of *Eucalyptus* as firewood, highlighting market opportunities for this biomass form. For this reason, this study fills a knowledge gap in wood storage research for these two forms of *Eucalyptus* biomass.

2. Materials and Methods

2.1. Studying Site

The research was conducted between February and September 2018 (8 months) at the experimental fields of CREA-IT (Council for Agricultural Research and Economics-Research Centre for Engineering and Agro-Food Processing) in Monterotondo (Rome, Italy—42°10′19′′ N latitude, 12°62′66′′ E longitude), characterized by a Mediterranean climate (Figure 1). The plants, harvested in February 2018, used for the study were obtained from a medium-rotation (5 years old) *Eucalyptus* plantation present at the CREA-IT experimental fields. The planting layout was 3 m × 2 m, with a total plant density of 1600 plants per hectare. The stand was grown on a flat area of about 1 ha, characterized by alluvial soil with a silty clay soil texture [26]. Two different storage systems were investigated: wood stem and firewood logs in mesh bags. Each storage system was tested under two different conditions: wood stems with and without branches and firewood logs in mesh bags outdoors and indoors.

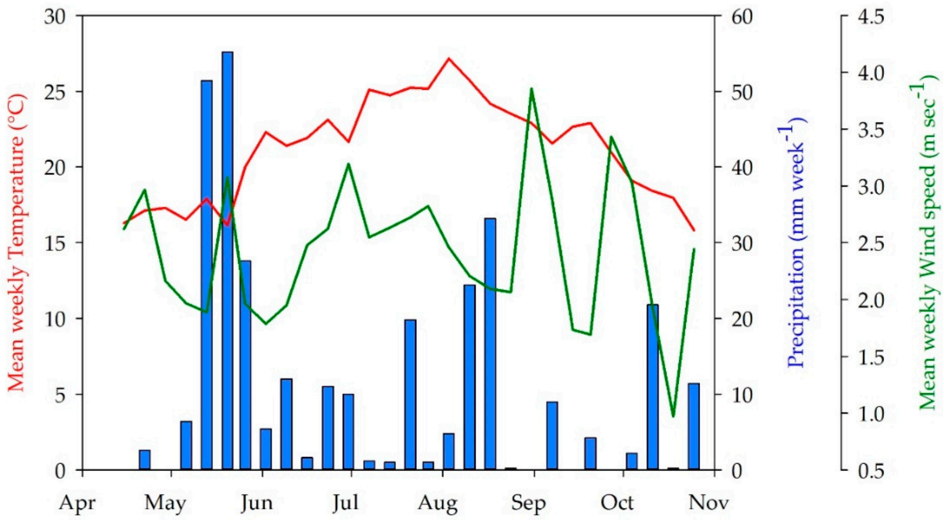

Figure 1. Weather data of the storage period. The red line represents the mean weekly temperature; blue bars are the cumulative weekly precipitation; the green line is the mean weekly wind speed.

2.2. Storage Systems

The four storage treatments of eucalyptus woody biomass examined in this research are:

- Outdoor storage of whole stems without branches (WS).
- Outdoor storage of whole stems with Branches (WSB).
- Open shed storage of firewood logs in mesh bags (OSF).
- Outdoor firewood logs in mesh bags (ODF).

2.2.1. Outdoor Storage of *Eucalyptus* Whole Stems with (WSB) and without (WS) Branches

Immediately after the plants' harvesting, the storage trial took place outdoors using 3.5 t of *Eucalyptus* plants, felled using a chainsaw and transported to the field edge with a tractor fork. Details of the harvesting operations, including fuel consumption, oil lubricant consumption, timing and number of workers employed were recorded with respect to felling, limbing and logging/stacking operations (Table 2). Half of the plants were de-branched and piled in two heaps (WS—Figure 2). Another two heaps were made with the remaining plants, which were left with branches and leaves (WSB—Figure 3). At felling date, each pile of trees was weighed using a dynamometer (model CS 1000N, PCE Italia Srl, Lucca, Italy—range of measurement 1000 kg and sensitivity 0.2 kg). The weight of each pile was measured every 30 days till the end of the storage period to calculate the mass variation due to losses of dry mass and moisture content reduction. In this regard, concurrently with the day of weighing, 10 samples of wood stem for each pile were randomly selected, according to the methodology proposed by Laurila and Lauhanen (2010) [27], to determine the moisture content following the international standard ISO 18134-1 [28]. The determination of the total moisture content of a test sample of solid biofuels was done by drying in an oven. The moisture content of solid biofuels is always reported based on the total mass of the test sample (dry basis). For calculation of moisture content, the following equation was used:

$$MC\ (\%) = \frac{W_{fb} - W_{db}}{W_{db}} \times 100 \quad (1)$$

where W_{fb} is the weight of the sample on fresh basis (g) and W_{db} is the weight of the sample on dry basis (g).

Table 2. Description of the operation time and consumption during the harvesting of *Eucalyptus* spp. plants in MRC.

Operation.	**Unit**	**Felling**	**Limbing**	**Logging and Stacking**
Tools		**Chainsaw**	**Chainsaw**	**Tractor with Fork**
Time	[sec tree^{-1}]	18	58	14
Fuel consumption	[KJ Kg^{-1}]	2.06	7.51	0.03
Oil lubricant consumption	[ml tree^{-1}]	1.6	5.6	
Worker	[*n*]	1	1	3

Figure 2. *Eucalyptus* whole-stem storage without branches (WS).

Figure 3. *Eucalyptus* whole-stem storage with branches (WSB).

Only wood stem was considered in this study in order to evaluate the effect of the leaves on wood drying by comparing the moisture content variation of plants with or without branches.

2.2.2. Firewood Logs in Meshed Bags: Outdoor (ODF) and Open Shed (OSF) Storages

After plant felling, 20 plants were cut using a circular saw (Rosselli, mod. Grizzly 700R) driven by the PTO of a 66-kW tractor. Around 1.2 t of firewood, of 30 cm length, was packed into 52 meshed plastic bags; half of this was stored outdoors and the other half was stored in an open shed (Figure 4). Each meshed bag was weighed using a dynamometer (model CS 1000N, PCE Italia S.r.l., Lucca, Italy—range of measurement 1000 kg and sensitivity 0.2 kg) at the beginning of the storage, every 30 days, and at the end of the storage period, in order to calculate the mass variation due to losses of dry mass and moisture content reduction. In this regard, concurrently with the day of weighing, three samples of firewood logs per treatment were randomly selected to determine the moisture content according to the international standard ISO 18134-1 [28] (for more details, see Section 2.2.1).

(**a**) (**b**)

Figure 4. Open shed (**a**—OSF) and outdoor (**b**—ODF) storage of firewood logs in mesh bags.

2.3. Climatic Data

The woody biomass stored outside (WS, WSB and ODF) was exposed to the same weather conditions, and the climatic parameters, such as temperature, precipitation, wind speed and wind direction were recorded during the entire storage period (8 months) using a weather cab (Davis, model Vantage Pro 2, CA, USA) placed in the proximity of the storage site and connected to a wireless net.

2.4. Statistical Analysis

Repeated measurement analyses of variance using dates and storage methods as factors were used for analyzing the moisture data obtained from the treatments. Pairwise multiple comparison was conducted with the Holm–Sidak method. The differences among the storage methods in dry matter loss were analyzed using ANOVA and Tukey post hoc test. Analysis were performed using PAST [29].

3. Results

3.1. Climatic Data

During the storage period, the total rainfall recorded was 665.8 mm. The mean temperature during the whole storage period was 17.97 °C, and the mean monthly rainfall was 73.98 mm. Maximum and minimum temperature were registered, respectively, in July (38.4 °C) and February (−8.7 °C), while the maximum amount of precipitation was recorded in March (179.4 mm) and the minimum in September (13.2 mm). The evolution of weather is shown in Figure 1.

3.2. Harvested Plants Characteristic

At time of harvest, after five years of cultivation, the mean height of the plants was 9.5 ± 1.31 m and the mean diameter was 10.07 ± 1.94 cm. The total weight of the plants was 70.12 ± 11.11 kg on average, the stem representing 56.64 ± 4.11% of the total plant. The moisture content was 50.56 ± 1.96%.

3.3. Moisture Dynamic and Dry Matter Loss

The four storage methods showed a similar moisture variation pattern (Figure 5). Among the storage methods, we found significant differences between ODF and OSF ($t = 6.187$, p-value < 0.01), and uncovered log and whole stem ($t = 4.668$, p-value $= 0.01$). Considering the time, at the beginning we observed a significant decrease in samples' moisture until July, then moisture reduction was not significant. In April, a significant difference was found between ODF and OSF ($t = 5.107$, p-value < 0.001). In July, significant differences were found between ODF and WSB ($t = 2.955$, p-value $= 0.03$). At the end of the experiment, the moisture was different only between debranched stems and OSF ($t = 3.029$, p-value $= 0.03$). In Autumn, an increase in moisture content of 4.33% and 1.3% was observed in WS and in the WSB piles, respectively.

Significant differences were found between the dry matter loss ($F = 10.758$, p-value < 0.001), with the highest loss observed for the whole stem storage (Figure 6).

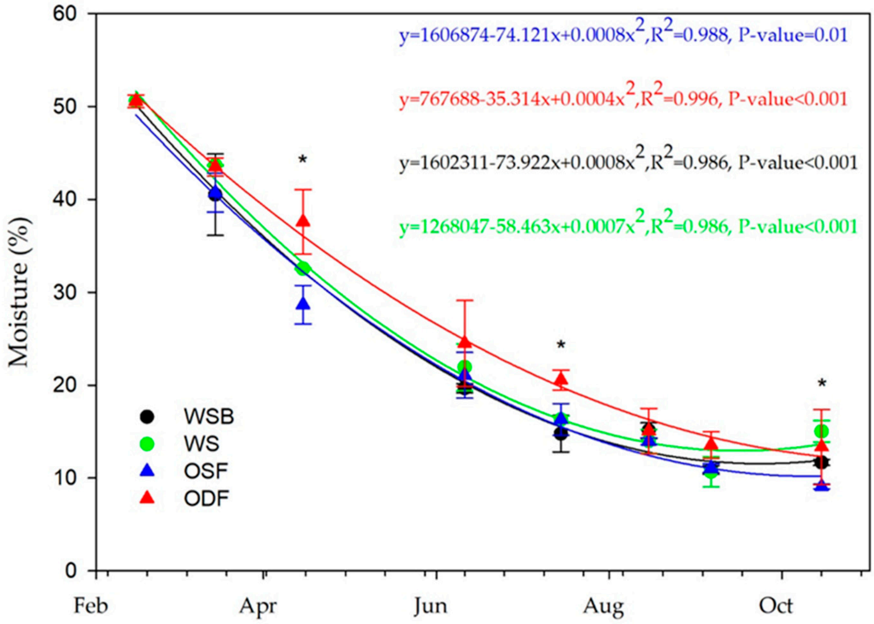

Figure 5. Moisture dynamic during the storage period. WS is the outdoor storage of whole stems without branches; WSB is the outdoor storage of whole stems with branches; OSF is the open shed storage of firewood logs in mesh bags; ODF is outdoor firewood logs in mesh bags (ODF). Differences between the storage methods in sampling date are indicated with *. Bar error represents standard deviation.

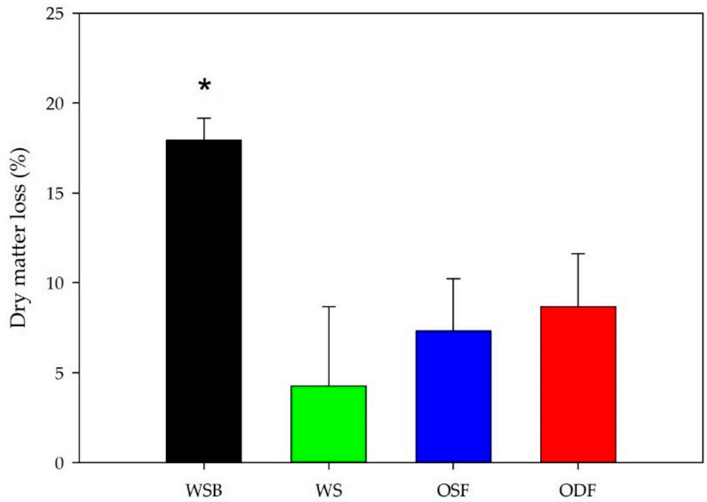

Figure 6. Dry matter loss for each storage method. WS is the outdoor storage of whole stems without branches; WSB is the outdoor storage of whole stems with Branches; OSF is the open shed storage of firewood logs in mesh bags; ODF is outdoor firewood logs in mesh bags (ODF). Differences between the storage method in sampling date are indicated with * (p-value < 0.05). Bar error represents standard deviation.

4. Discussion

Eucalyptus biomass can satisfy, considering its high growth potential and relative hardness [10], the growing firewood demand [11]. Hence, it is crucial to provide the best storage system for placing products on the market which can compete with classical fuel wood (oak, beech). Indeed, storage is fundamental to reach commercial moisture and reduce dry matter loss. Moisture reduction is a crucial objective for storing biomass for direct energy generation. In wet biomass, energy produced by combustion is used to evaporate water from the material, thus reducing the usable energy available or the fuel's net heating value. During the storage period, ODF showed higher moisture values than

OSF. Considering that even whole (WSB) and debranched (WS) stems were stored outside, this result underlines that moisture reduction in stored biomass is related to local climatic conditions, material composition, form of biomass, pile size and permeability (compaction), and the activities that affect the internal temperature of the pile [24]. However, at the end of the storage period, the four options reached a similar moisture to the commercial one of the fuel wood (around 15%). Considering that, from July, moisture remained stable, the storage time until the end of September would have avoided the autumnal precipitation, which caused, for the debranched stems, an increase of 4.4% in the moisture. Hence, in similar climatic conditions, it is more convenient to store until the end of summer, to avoid a moisture increase due to autumn precipitation. Indeed, the seasons of harvest and storage affect the final moisture content of harvest residues. Especially for biomass stored outdoors, the seasoning is crucial. Various studies of biomass storage have shown that the lowest moisture content was reached around the end of summer. On the contrary, prolonging outdoor storage until winter leads to an increase in biomass moisture content [30,31]. The comparison of the WSB and WS moisture dynamics suggested that leaves did not affect transpiration. The most significant loss of moisture resulting from transpirational drying occurs within 36 h of felling [32]. At the end of the storage period, the four systems reached the same moisture value. All the storage systems analysed in the manuscript reached lower moisture values than 31% and 40% of wood chips stored in covered and uncovered piles, respectively [18]. Dry matter loss can be affected by biological degradation [24] and in turn affect the energetic potential of the biomass. The dry matter loss of the log systems showed values around 1% of dry matter loss per month, with a very similar mass loss estimated for pulp chips stored outdoors in North America [33], as well as for the 1% of birch chips stored under cover in Norway [34] for different climatic conditions and characteristics of the biomass. Regarding dry matter losses, no differences were found among firewood storage systems, while differences were found between whole plant storage systems. Results suggest that no impact on the dry matter losses is given by the type of firewood storage, but the debranching of the whole stem is a crucial aspect. The dry matter losses of the four storage systems reported in this study are comparable with those of woodchip storage in similar conditions [18]. Results achieved with debranched stems are in line with those obtained in other studies, such as in the storage experience of whole young trees of downy birch performed in Sweden [35]. On the other hand, the high losses identified in WSB piles should be ascribed to the drying and total falling process of the leaves, as the initial amount of leaf biomass of eucalyptus trees was very high (about 44% of the tree was branches and leaves). Moreover, it is important to underline that in the WS storage system all the potential energy of branches was lost. However, these organs are richer in bark than stems, hence producing more ash after combustion.

5. Conclusions

Eucalyptus biomass is a species of particular interest, especially for MRC. Storage alternatives to piles of wood chips were investigated to limit biomass degradation and find easier handling strategies without affecting the storage time and the quality of the biomass.

The research has studied the variation in moisture and dry matter loss resulting from the storage of bagged logs and whole plants from a MRC *Eucalyptus* plantation in Central Italy. In particular, two type of storage system were adopted for each biomass product: open shed (OSF) and outdoor (ODF) storage of firewood logs in mesh bags and outdoor debranched (WS) and whole stem (WSB) plants. For this reason, this study represents a novelty due to the usage of alternative fast growing species, such as *Eucalyptus*, for fire wood. Consequently, we analyzed innovative storage systems suitable for the firewood market.

At the end of the 8 months’ storage (September 2018), the dry matter losses were lower than 10%, except for WSB treatment (17%), and all the treatments resulted in similar moisture content (around 15%). The trend of the dry matter losses was similar to other studies focused on the storage of wood chips in piles.

In conclusion, producing firewood directly at harvesting time opens new market opportunities, considering the qualitative and quantitative characteristics of the biomass after storage. The storage of whole plants, in the presence of sufficient space at the edge of the field (given the greater volumes generated by the presence of branches) can represent an interesting alternative to WS due to the lack of the limbing phase, and economic savings would result. Moreover, at the end of storage period (which in Mediterranean climates according to the data could be in July), the presence of branches that would normally be lost would represent an additional quantity of biomass available to produce wood chips or firewood. Further studies should investigate the economic feasibility of such MRF storage systems by comparing them with more traditional wood chip storage methods.

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