Biomass and Bioenergy 150 (2021) 106109

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Fuel quality and dry matter losses of stored wood chips - Influence of cover material

Erik Anerud [a,*], Dan Bergström [a], Johanna Routa [b], Lars Eliasson [c]

[a] Department of Forest Biomaterials and Technology, Swedish University of Agricultural Science, Forest Biomaterials and Technology, SE-901 83, Umeå, Sweden
[b] Natural Resources Institute Finland, Luke, Yliopistokatu 6B, 80100, Joensuu, Finland
[c] The Forestry Research Institute of Sweden, Uppsala Science Park, SE-75183, Uppsala, Sweden

ARTICLE INFO

Keywords:
Biomass
Energy content
Forest fuel
Fuel quality
Wood chip storage

ABSTRACT

Irregular seasonal demand from heat- and combined heat and power plants means that outdoor storage of forest fuels is an inevitable step in the forest fuel supply chain. Storage of fresh comminuted biomass render substantial dry matter and energy losses. Covering can protect wood chips from rewetting, leading to a higher net calorific value and lower dry matter losses, and thus increase the amount of available energy. This study examined the combined effect of covering material on fuel quality and the amount available energy from wood chips stored in a full-scale pile. The combined changes in fuel quality and dry matter loss reduced the amount of accessible energy by 9.8% in the uncovered part, by 5.6% when covered with water proof or light semi-permeable cover materials and by 1.0% when covered with a thicker semi permeable material. Fuel quality of wood chips can be improved by covering the piles during storage but the gain is affected by the type of cover material. Seasonal storage in properly covered chip piles facilitate an increased annual utilisation of chippers and chip trucks which reduces overall biomass supply chain cost.

1. Introduction

In the Nordic countries, forest harvesting is a year-round activity to supply saw mills and pulp mills with wood. This generates a continuous stream of logging residues that can be used as fuel. In the fuel consuming heat plants and combined heat and power (CHP) plants demand for fuel is irregular, although the greatest demand for fuels occurs during the cold season (November–February). This means that outdoor storage of forest fuels is an inevitable step in the forest fuel supply chain. There is also a possibility that seasonal storage of comminuted forest fuels may reduce supply chain costs due to more efficient utilisation of the equipment used in the supply chain throughout the year [1–3]. Thus, this would however entail large-scale storage of wood chips produced during the low-demand period until the high-demand period; which on one hand would increase the ability to meet sudden increases in demand, but on the other hand add additional costs for handling of the material as well as storage losses and quality changes in the stored fuel.

Storage of comminuted biomass (wood chips) incurs risks such as large dry matter losses (DML) and energy content losses as well as the risk of self-ignition [4]. These risks can be minimised by measures for managing moisture content (M); this is a key issue since it affects both biological and chemical processes as well as the available amount of energy [5]. Covering wood fuel piles can protect the biomass from rewetting by precipitation and enhance natural drying [6–11], which increases the net calorific value (Q) expressed on wet basis. The effect of covering depends on several factors including the ventilation and rain protection properties of the cover, the amount of precipitation and how well water vapour and heat disperse during storage so that condensation under the cover is avoided. In small and medium sized storages, the storage can be either under roof, e.g. in a chip barn, or outdoors as chip piles [12]. For large scale storage of several thousand of tonnes of chips the only realistic option is to use outside storage in chip piles. While storage in well ventilated chip barns have proved an effective, although expensive, way of protecting the chips from rain and letting the moisture in the piles evaporate. Management of M in outdoor storages is an unsolved issue.

Covering the piles protects them from rain and snow but may also act as a lid preserving the moisture in the pile, so that it only gets redistributed within the pile during the storage period. To make matters worse both capillary rise of soil moisture and surface runoff of rain water may increase the amount of M in the piles during the storage period.

Wetzel et al. (2017) reported that M in a chip pile increased from

* Corresponding author.
E-mail address: erik.anerud@slu.se (E. Anerud).

https://doi.org/10.1016/j.biombioe.2021.106109
Received 17 December 2020; Received in revised form 6 April 2021; Accepted 28 April 2021

49% to 65% during one year of storage when the pile was covered with a plastic tarp [8] and Spinelli et al. (2007) showed that sealing wood chips in a trench led to anaerobic fermentation [13]. The ventilation of covered piles therefore seems to be almost as important as the covering. Early studies where a wooden lattice was used to create a distance between the tarpaulin and the chip piles and where the tops of the piles were uncovered showed promising results but were impractical [12]. A decline in M from 52% to 45% was reported after storage for 6 months when wood fuel chips were covered with a semi-permeable sheet [10] and the use of paper-based tarps and the breathable cover material (Toptex) resulted in less degradation of biomass [8–10].

Covering can protect wood chips from rewetting and facilitate natural drying which leading to a higher Q, referred to wet basis, and lower DML, and thus increase the amount of available energy. This effect can be reinforced by choosing a cover material that allows moisture to evaporate from the piles [10,14]. However, the combined effect of covering material on the fuel quality and the amount of available energy has not been reported in the literature.

The objective of this study was to evaluate the effects of five covering materials on M, DML, Q, and energy content of wood chips during long-term storage.

2. Materials and methods

2.1. Wood chips and storage location

The storage trial was performed in Bensjö, Sweden (62°42′N; 15°27′E), from mid-June 2014 to December 2015. Stored Norway spruce logs (*Picea abies* (L.) H. Karst) were chipped using a large disc-chipper (Erjo 2300) and homogenised (mixed with a wheel loader) before the construction of piles. Most of the chips produced were within the range 8 mm–45 mm and classified as P45 according to SS EN 14961–1 [15].

The storage pile was oriented with its long side perpendicular to the prevailing wind direction, which also maximised sun exposure of the pile during the storage period (Fig. 1A). In each half of the pile, six 6 m wide sections were randomly allotted as either uncovered control or to be covered with one of the studied cover materials (Table 1, Fig. 1C). The cover materials (Table 1.) can be divided into two groups: 1) waterproof ones, not permitting evaporation, and 2) water-resistant materials that permit evaporation (i.e. are breathable like e.g. GoreTex).

2.2. Field trial structure and sampling

The experimental setup consisted of one full-scale wood chip pile, which was constructed in mid-June 2014 using a conveyor (Fig. 2). The dimensions of the pile were 15.0 m (base) × 100.0 m (length) × 6.5 m (height), with an estimated volume of 4500 m^3 (ca. 900 Mg, ton DM). The cross-section of the pile was almost triangular. The main axis of the pile was aligned in an east-west direction (Fig. 1A).

The pile was divided into two blocks, from which final sampling was conducted after three months for block 1 and after six months for block 2. Each block was divided into six sections (Fig. 1B), five sections covered with different materials (Table 1) and one uncovered section. In each section, seven sampling points (Fig. 1C.) were located. At each sampling point were six samples collected for determination of M, ash content (A), Q and DML. Half of the sampled material was reserved as a corresponding sub-sample of each sample bag during bag filling for further analysis of the initial characteristics of the wood chips. The other half was placed into net bags (2.8 mm mesh size), weighed (0.01 g accuracy) and returned to the sampling point. These samples remained in the pile until final sampling of the block. For the determination of particle size distribution, a 10 l bucket was collected from each sector in block 2 during construction and collection of sampling from the exposed section in block 2. After storage, net bags collected from the exposed sectors were cleaned by removal of attached debris before weighed. In total, 504 samples for the determination of M, A, and Q, 252 samples for DML and 12 samples for particle size distribution, were taken.

Tinytag ® temperature sensors, each with a sampling frequency of 1 h, were used to monitor the temperature at the 5.5 m level, sampling point 7, within each section in block 2 (Fig. 1C). For each section, daily mean temperature and the temperature sum (t > 0 °C, based on daily mean temperature) was calculated.

In the lab, M (w.b.), A (d.b.) and Q (w.b.) of the sampled chips were determined according to standard methods (Table 2). Particle size reduction was performed using a Retsch mill equipped with a sieve (mesh size: 0.25 mm). The initial DM of the samples in the net bags was used as the basis for the calculation of DML, which was expressed as the mass loss (%) on a dry basis.

Recovered energy, i.e. the energy available after storage, was calculated as:

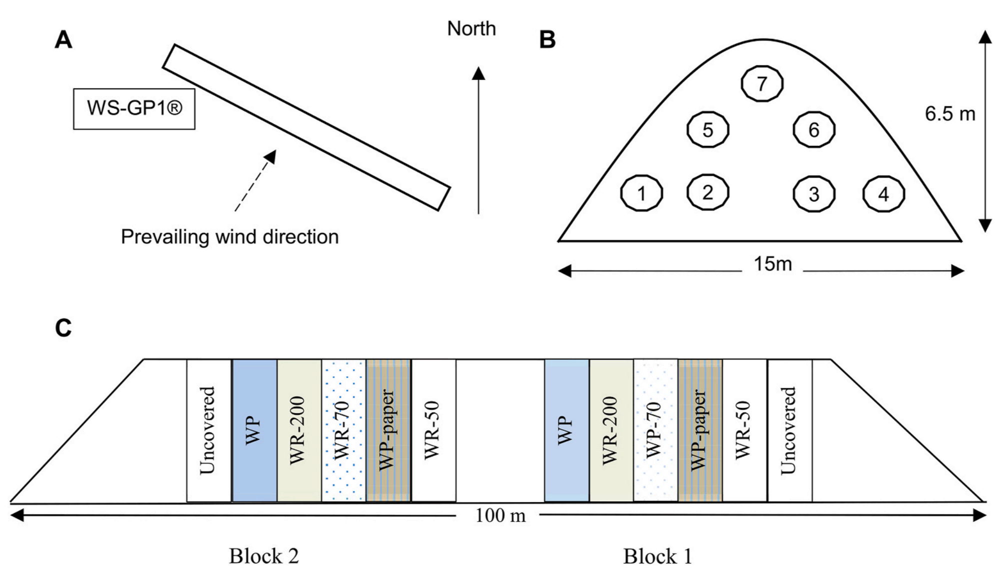

Fig. 1. A; Orientation of piles, showing the prevailing wind direction and the relative position of the mobile weather station (WS-GP1®). B; Cross-section of the experimental pile, showing sampling points 1–7. C; Side view of an experimental pile, showing the covered sections and the uncovered reference. TinyTag® temperature sensors were placed at sampling point 7 within section block 2.

Table 1
General description of the studied cover materials.

Name	Treatment	Type of material	Weight gm^{-2}	Water resistance	Breathable
PS-energy cover	WR-55	Heat treated polypropylene	55	Water resistant	Yes
Windy	WR-70	Woven & coated polypropylene	70	Water resistant	Yes
TopTex	WR-200	Non-woven propylene	200	Water resistant	Yes
Tarpaulin	WP	Woven and coated polyethene	250	Waterproof	No
Walki biomass cover	WP-paper	Reinforced paper-based laminate	247	Waterproof	No

Fig. 2. The wood chip pile covered with different materials prior to storage.

Table 2
Standards used for sampling, sample preparation, classification and determination of fuel characteristics.

	Standard	Reference
Sampling	SS-EN 14778: 2011	[16]
Sample preparation	SS-EN 14780:2011	[17]
Fuel specifications and classes	SS-EN 14961–1:2010	[15]
Determination:		
Particle size distribution	SS-EN 15149–1:2010	[18]
Moisture content (M) expressed on a wet weight basis	SS-EN 14774: 2009	[19]
Ash content (A) expressed on dry weight basis	SS-EN 14775:2009	[20]
Gross calorific value	SS-EN 14918:2010	[21]
Net calorific value (Q) expressed on a wet weight basis	SS-EN 14918:2010	[21]

$$E_r = \frac{(1-0.01*DML)}{(1-0.01*M)}*Q \quad \text{(Equation 1)}$$

where E_r is recovered energy per initial mass, DML is dry matter loss as a relative share of initial mass, M is moisture content on a wet basis, and Q is net calorific value on a wet basis.

The economic value of stored material was calculated using a price of 190 SEK per MWh, which corresponds to the average price for solid by-products in 2014 (Wood fuel- and peat prices, 2014), converted to EUR using the exchange rate in December 2014, giving a price of 21.3 EUR per MWh.

2.3. Meteorological data for the storage site

Throughout the storage period, a mobile weather station (WS-GP1®) was positioned 10 m from the south side of the pile to gather meteorological data including measurements of temperature and precipitation, with a sampling frequency of 1 h (Fig. 1a). Historical data (30-year averages) on local weather conditions, based on values for Hunge (62°44′N; 15°6′E), 19 km from Bensjö, were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The mean ambient temperature during the pile construction in June 2014 was 10.6 °C. The mean monthly temperature during storage did not significantly differ from the mean long-term value obtained from SMHI. The cumulative precipitation during the six month storage period was 306 mm, which was 55 mm lower than the 30-year average for the region. During the first three months of storage, the cumulative precipitation was 140 mm. The cumulative precipitation in October (99 mm) was more than twice the 30-year average for the month, which was due to two intense rain events (>15 mm) during this period.

2.4. Statistical analysis

The experiment was designed as a randomised factorial experiment. The assumption of homogeneity of variances between sections was tested using Levene's test. Analysis of variance (ANOVA) was performed using a general linear model (GLM) followed by Tukey's highly significant difference (HSD) test. The dependent variables (M, DML, A, Q, and E_r) were analysed with respect to the factors cover material (6 treatments) and storage duration (3 levels). All analyses were performed using STATISTICA v.10 and differences between factors and their interactions were considered significant at $p \leq 0.05$.

Table 3
Mean moisture content (%, w.b.) and 95% level of confidence (in brackets) of wood chips during storage. Different letters within rows indicate significant differences between treatments regarding cover material and different Greek letters within columns indicate significant differences between treatments regarding storage duration.

Date	Uncovered	WP	WP-paper	WR-70	WR-55	WR-200
2014-06-17	26.9 (0.7) aα	27.1 (0.6)aα	27.5 (0.5)aα	27.3 (0.6)aα	27.1 (0.6)aα	27.0 (0.5)aα
2014-09-17	29.7 (0.6) aβ	27.1 (0.2)bα	27.3 (0.3)bα	27.4 (0.6)bα	27.1 (0.5)bα	26.0 (0.5)cβ
2014-12-14	33.5 (1.0) aγ	27.1 (0.7)bα	27.2 (0.3)bα	28.8 (1.0)cα	28.3 (1.2)cα	24.6 (0.6)dγ

3. Results

3.1. Chip quality prior to storage

The initial M, A and Q of the piled chips were, on average ($n = 252$), 27.2% ± 1.8 (SD) (Table 2), 0.73% ± 0.05 (SD) (Table 4), and 12.89 $MJkg^{-1}$ ± 0.4 (SD), respectively (Table 4). There were no significant differences in these properties between treatments. Most of the chips produced were within the range 8 mm–45 mm (Fig. 3) in particle size and were classified as P45 according to SS EN 149611 [15]. After 6 months of storage the average amount of particles <8 mm decreased.

3.2. Temperature development within the pile

In general and irrespective of cover material, the temperature at 5.5 m increased from 8.5 °C to around 20 °C within the first two weeks (Fig. 4). During the first 30 days of storage, the temperature in the uncovered section and the section covered with the tarpaulin (WP) increased to 27 °C, while the sections covered with WR-70, WR-55 and WP-paper reached 24 °C and the section covered with WR-200 remained at 20 °C. The highest temperatures were observed within the uncovered section, followed by the section covered with tarpaulin. The average temperature in all sections stabilised and remained relatively steady between day 30 and day 60. Thereafter, the temperature gradually decreased to 15 °C in the section covered with WR-200, while all other sections exhibited only small temperature changes.

Three significantly different levels of temperature sums were obtained after storage for 6 months. On average, after storage for 6 months, the temperature sum in the uncovered section and the section covered with WP was 4745 °C, in the section covered with WR-200 it was 3020 °C, and in WR-70, WR-55 and WP-paper it was 4076 °C.

3.3. Moisture content (M)

During the first three months, average M increased significantly to 29.7% ± 1.3 (SD) when uncovered and decreased significantly to 26.0% ± 1.2 (SD) when the wood chips were covered with WR-200 (Table 3). No significant changes in M were observed for sections covered with the other materials. After storage for three more months, average M significantly increased to 33.5% in the uncovered section, while the average M in the section covered with WR-200 significantly decreased to 24.6%. Average M in all the other sections remained unchanged. After six months of storage, the uncovered section ($p < 0.01$, $R^2 = 0.83$) and the WP covered section ($p = 0.02$, $R^2 = 0.24$) exhibited significant negative correlations between M and vertical position within the pile, i.e. the top was wetter than the base, while the section covered with WR-200 exhibited a significant ($p < 0.01$, $R^2 = 0.68$) positive, correlation (Fig. 5). No significant correlation between M and vertical position for treatments WP-paper, WR-70 and WR-55 was observed. Thus, in case of the water-resistant materials, moisture was not concentrated in the top layer of the pile. Accordingly, the properties of the individual materials have a clear effect on moisture distribution within the pile.

3.4. Dry matter losses (DML)

Covering the pile with WR-200 resulted in an average DML of 1.4% after storage for three months, while the average loss within all other sections was 2.5%. By the end of the storage trial, the average DML had significantly increased in all sections to 6.7%, 2.5% and 4.7% within the uncovered section, the WR-200 covered section and all other sections, respectively. The uncovered section and the section covered with the tarpaulin (WP) showed a significant ($p < 0.01$, $R^2 = 0.80$) positive correlation between sample height level and DML.

3.5. Ash content (A) and net calorific value (Q)

In general, A increased significantly ($p < 0.05$) in all sections after storage for 6 months (Table 4), except for the sections covered with WR-70 and WR-55. The initial gross calorific value, expressed on dry basis ($q_{V,gr,d}$) was significantly ($p < 0.01$, $R^2 = 0.79$) negatively correlated with A. However, this correlation decreased to $R^2 = 0.42$ after storage for 6 months. The mean initial Q of the material was 12.89 $MJkg^{-1}$ ± 0.04 (SD). The Q within the uncovered section decreased to 12.41 $MJkg^{-1}$ after three months of storage, while no significant changes were found for the other sections. Storage for 6 months led to decreased Q when stored uncovered or covered with WR-70, to increased Q when covered with WR-200, while there was no significant difference in Q for the other cover materials.

3.6. Recovered energy after storage and economic value

The initial amount of accessible energy (E_r) derived from initial dry mass was 17.69 MJ ± 0.27 (SD) (Fig. 6). The value of E_r decreased significantly by 0.39 MJ after storage for 3 months except for the section covered with WR-200. Further storage (total 6 months) decreased E_r to 15.95 MJ ± 0.69 (SD) in the uncovered part and to 16.70 MJ ± 0.47 (SD) in all covered sections except for the section covered with WR-200, which decreased to 17.48 MJ ± 0.17 (SD). Assuming an energy price of 21.3 € per MWh, the energy changes observed were equivalent to an economic loss during storage of 10.3 € per oven-dry ton (9.8%) for uncovered wood chips. With cover, the economic loss was equivalent to 5.9 € (5.6%) per oven-dry ton in all treatments, except for WR-200, were it was 1.2 € (1.2%).

4. Discussion

The storage trial was designed to mimic commercial storage conditions and a full-scale pile were constructed by chips from low quality logs, which is a common forest fuel in Nordics. The pile had the same height and ratio between surface area and volume as used in commercial storage. The use of a conveyer during construction was effective and made it possible to shape the pile so that it had a triangular cross-section, with a sharp top at a height of 6.5 m, and the size and shape were identical for all sections/treatments. The material was stored from June to December, which is a usual period given the customer demand [22]; and the ambient storage conditions, e.g. precipitation per m^3 of stored fuel, temperature etc., were representative for the period. The temperature change within the wood chip pile was less pronounced compared

Table 4
Average ash content (A, d.b.) and net calorific value (Q, w.b). Different letters within rows indicate significant differences between cover materials and different Greek letters down columns indicate significant differences between storage durations.

	Date	Uncovered	WP	WP-paper	WR-70	WR-55	WR-200
A (%, d.b.)	2014-06-17	0.72aα	0.73aα	0.74aα	0,80aα	0.73aα	0.65aα
	2014-09-17	0.96aα	1.06aα	0.99aα	0.96aα	0.99aα	0.96aα
	2014-12-14	1.37aβ	1.31aβ	1.18aβ	1.18aα	1.13aα	1.16aβ
Q ($MJkg^{-1}$, w.b.)	2014-06-17	12.95aα	12.89aα	12.83aα	12.86aα	12.93aα	12.88aα
	2014-09-17	12.41aβ	12.93bα	12.91bα	12.94bα	12.95bα	13.24bα
	2014-12-14	11.37aγ	12.81bα	12.75bα	12.46bβ	12.56bα	13.51cβ

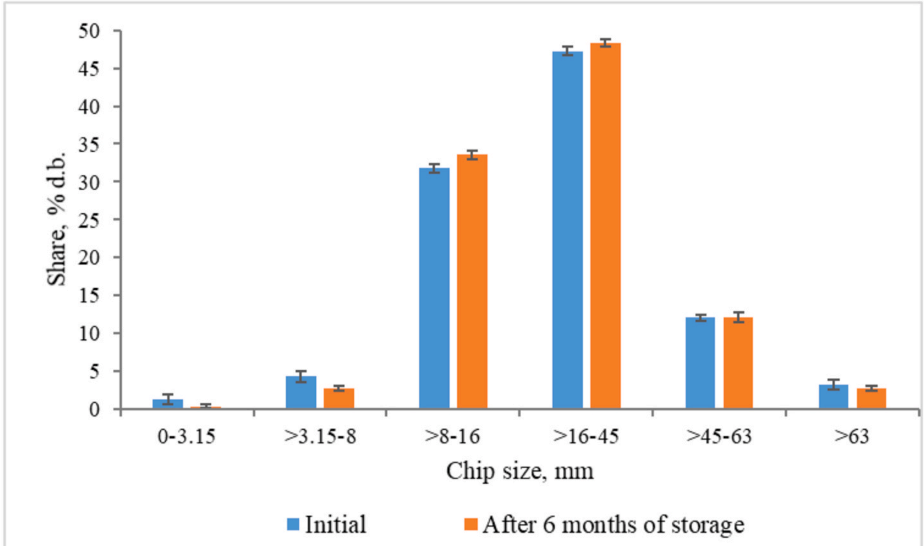

Fig. 3. Average particle size distribution during construction (n = 6) and after storage (n = 6) for 6 months.

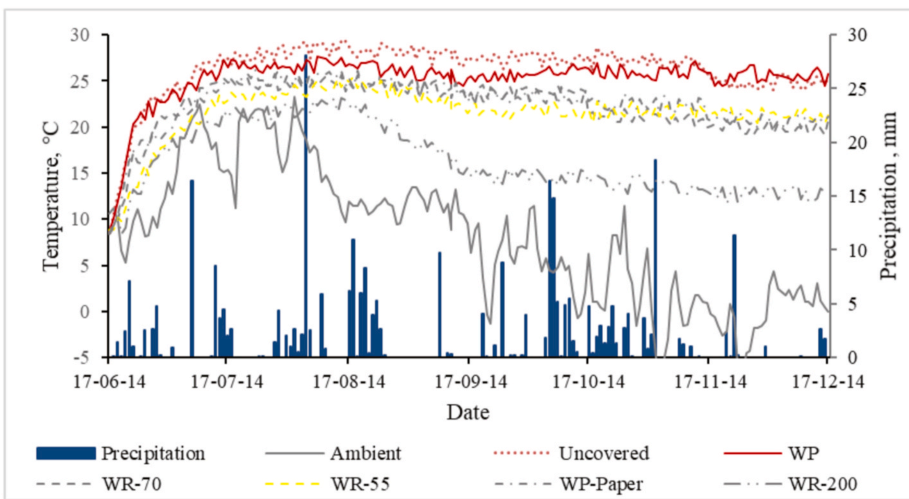

Fig. 4. Ambient temperature and temperature changes within uncovered and covered wood chip pile sections.

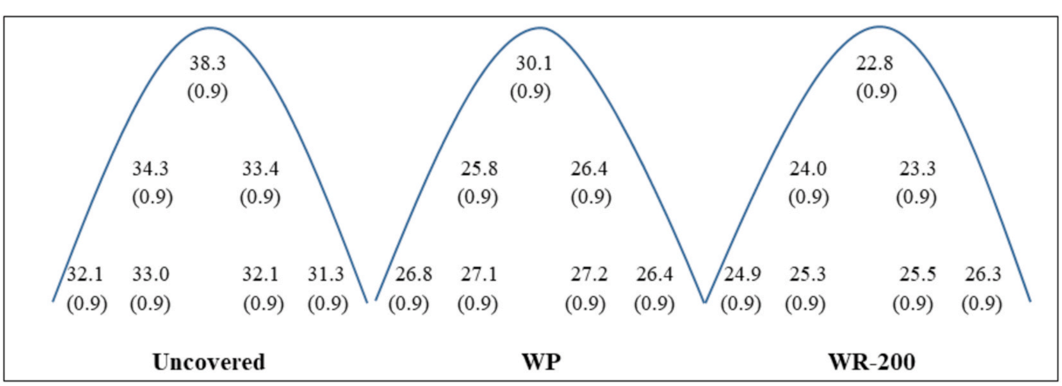

Fig. 5. Mean moisture content (%, w.b.) and 95% level of confidence (in brackets) at the sampling points after 6 months of storage for treatments Uncovered, WP and WR-200.

to earlier studies, but followed a typical pattern, which indicated that the biological- and chemical activities, and thus, the progression of the processes associated with temperature change and dry matter losses were normal (cf [23]). The conditions of our trial are valid for other northern regions around the globe, but caution is advised when generalizing results as differences in raw material properties may affect

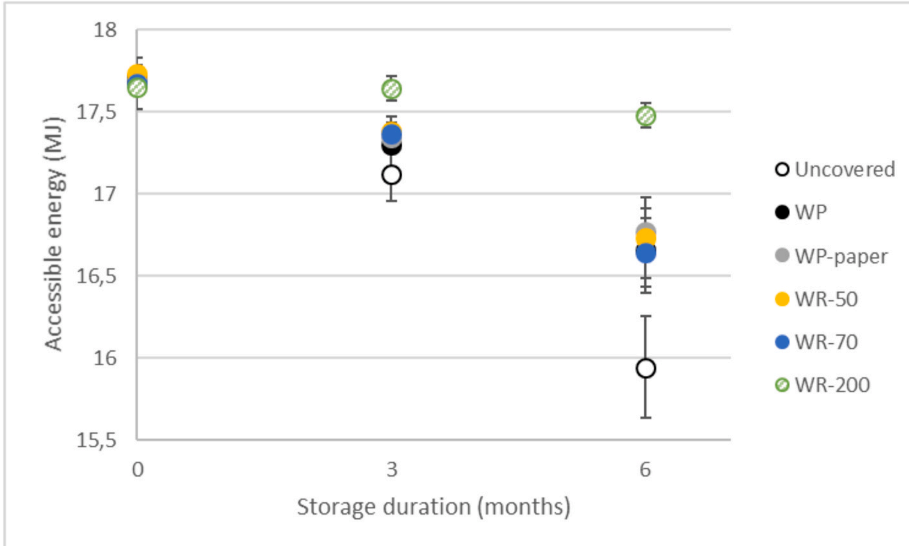

Fig. 6. Mean amount of accessible energy (MJ) derived from 1 kg initial dry material and 95% level of confidence.

storage processes and individual results. Therefore, they should be considered as indicative until validated by further trials.

The design of the storage trial made it possible to compare the effect of the type of cover material used on fuel quality and E_r after storage in a cost-effective manner. The results would be more robust if there had been replicates of the piles. However, this necessitates an experiment that is at least three times as big, which would be labour intensive, costly, both in terms of research funds and for the host company and would involve considerably more material. Most probably, it would not render vastly different results, at least not in relative terms between treatments.

The initial fuel characteristics were homogenous and, after storage, variations in M, A, Q and E_r can be attributed to the cover materials. The chips were produced from stored logs and the proportion of fines (i.e. particles <3.15 mm) and the share of green mass, was low, which made the substrate relatively unattractive to wood degrading microorganisms. The initial M of the chips was 27.2%, which is low compared to M for freshly harvested biomass (ca. 50%) and lower than M observed in other storage trials [6,7,11,24–28] and at such a low M microbial activity might already be largely inhibited [23].

According to Thörnqvist (1985), temperature changes within the material are positively correlated with pile height and size [29]. However, this does not explain why temperature changes in our trials were lower than in similar studies [11,30–32]. Thus, the low M and the less nutrient-rich biomass are a more likely explanation for the quite moderate temperature increase within the pile. The temperature sum during storage showed three distinctive patterns, which indicates differences in biological activity depending on the different cover materials. This difference could partly be attributed to rewetting by precipitation, condensation and DML.

During storage, the uncovered section was clearly rewetted at the surface and covering the pile with a waterproof material led to redistribution of M, although only significantly for the tarpaulin cover (WP). The apparent difference between WP and WP-Paper may be an effect of the width of the cover material, where the tarpaulin used in WP was wide enough to cover the full section width while two stripes of WP-Paper was used to cover the full width of a section, thus creating an overlapping area in the centre of the section that not was completely gas-tight. Among the water-resistant materials, M decreased significantly at the top surface when covered with WR-200, while no such effect could be observed for the two lighter materials. This is most likely an effect of different degrees of water resistance and breathability among the tested WR materials. If a depression in the pile is formed, so the water cannot run off, all the tested WR materials will let water permeate, but the speed of this process depends on the material properties. The redistribution of moisture within piles is in agreement with published findings for wood chips stored in small piles [33].

As expected, DML was highest in moist areas, and thus in particular within the uncovered top level of the control, while low DML was observed in dry material, i.e. when M was 22–25%. This is in agreement with previous findings [10]. As an effect the variation in DML within a section increased with the variation in M. Compared to the uncovered reference, that had a monthly DML of 0.83% in the first and 1.37% in the second tree month period, the best cover material,WR-200, reduced the monthly losses by 44% (0.37% points/month) in the first and 73% (1.0% point/month) in the second three months-period. Similar effects of covering with the material used in WR-200 have been found in earlier studies [7,9,10,14,24,28] although the magnitude of the effect varies. The difference between the cover materials in DML was large, and WR-200 reduced the DML compared to all the other materials by 44% after 3 months of storage, and 47% after 6 months. As longer storage times may occur in practice, these differences could be even greater.

Thus, managing M is a key issue since it affects fuel quality and the amount of available energy. Reducing M reduces losses of both DM and energy during storage. Variations in initial $q_{Vgr,\ d}$ could be explained by variation in A. However, variations in $q_{Vgr,\ d}$ after storage include changes due to DML and the increase in A observed could be explained by DML. E_r (ignoring the effects of possible recondensation at CHP plants) was calculated from the individual sample parameters M and Q, determined according to standard methods. In addition, as individual sample M and mass, taken before and after storage, were used for the calculation of DML losses, these never became negative and variation in parameters M and Q were captured in the calculated value for E_r.

In general, the total amount of available energy decreased in all sections after storage, except when wood chips were covered with a semi-permeable material. However, covering, irrespective of material, led to lower DML and higher E_r than when wood chips were stored uncovered. Thus, covering the chips preserved energy and prevented an extensive loss due to rewetting and DML, meaning preserving value. However, as the type of cover had a significant effect on the extent to which value that was saved and earlier studies showed that unventilated waterproof materials can have a detrimental effect on M and thus value [15], breathable water resistant covers are recommended. The present study was conducted in one location and covered with five materials used or proposed as biomass cover, of which WR70 mainly is intended as a windbreaker/moisture seal behind the outer wall of buildings. As there is other materials that might be suitable for the purpose and storage conditions, there is a need for further studies of possible cover materials for wood chip piles.

Our results show that there are economic gains by covering stored wood chips, especially if the storage time is long. However, profitably is not only a question of reduced storage losses and cost of the cover material, but also of costs for installing and removing the cover from piles and the storage time. A further question, of both economic and environmental interest, is whether there is a possibility to reuse the covers or if they have to be considered spent after the storage is ended. Future studies are required to quantify handling costs, to evaluate alternative methods for covering piles, as well as how to handle the cover material when it is removed and if it is possible to reuse it. In areas where the piles are covered by snow at the time when the material is sent to the customer, the cover, depending on cover material, can be either a help or a nuisance when the snow is removed from the pile. Furthermore, as the choice of cover material affects the surface moisture in the pile, this implies a possibility to reduce the risk of outer layer freezing which is undesirable, as lumps of frozen chips are not accepted by the heating plants, due to the disturbances they cause when feeding the boiler [34].

5. Conclusions

Further development of wood chip storage systems minimising biomass losses are of great importance to reach a reliable and economically efficient supply of forest fuels to the energy sector. This study clearly shows that covering wood chip piles has a positive effect on DML, especially if the material are stored for longer time, which was expected (cf [7]). The difference between cover materials in cumulative DML was large, and WR-200 reduced the DML compared to all the other cover materials with more than 40% after both 3 and 6 months. In terms of fuel quality and economic outcome covering wood chips, and especially when using the most effective cover material, increase fuel quality and reduce economic losses by facilitating drying and preventing DML. As the results originates from only one location in Sweden, further studies are needed to validate the results.

Acknowledgements

This study was funded by the ESS (Efficient Forest Fuel Systems) 2011–2015 research programme, which was funded by the Swedish Energy Agency and the Swedish forest sector. We would also like to thank SCA for their support when establishing and conducting the trial.

References

[1] J. Windisch, K. Väätäinen, P. Anttila, M. Nivala, J. Laitila, A. Asikainen, L. Sikanen, Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain, Appl. Energy 149 (2015) 315–325.

[2] A. Eriksson, L. Eliasson, L. Sikanen, P.-A. Hansson, R. Jirjis, Evaluation of delivery strategies for forest fuels applying a model for Weather-driven Analysis of Forest Fuel Systems (WAFFS), Appl. Energy 188 (2017) 420–430.

[3] K. Väätäinen, R. Prinz, J. Malinen, J. Laitila, L. Sikanen, Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant, Gcb Bioenergy 9 (11) (2017) 1657–1673.

[4] R. Jirjis, Storage and drying of wood fuel, Biomass Bioenergy 9 (1–5) (1995) 181–190.

[5] E. Anerud, S. Krigstin, J. Routa, H. Brännström, M. Arshadi, C. Helmeste, D. Bergström, G. Egnell, Dry Matter Losses during Biomass Storage -Measures to Minimize Feedstock Degradation, IEA Bioenergy, 2019.

[6] M. Manzone, P. Balsari, R. Spinelli, Small-scale storage techniques for fuel chips from short rotation forestry, Fuel 109 (2013) 687–692.

[7] L. Pari, M. Brambilla, C. Bisaglia, A. Del Giudice, S. Croce, M. Salerno, F. Gallucci, Poplar wood chip storage: effect of particle size and breathable covering on drying dynamics and biofuel quality, Biomass Bioenergy 81 (2015) 282–287.

[8] S. Wetzel, S. Volpe, J. Damianopoulos, S. Krigstin, Can biomass quality Be preserved through tarping comminuted roadside biomass piles? Forests 8 (9) (2017), 305.

[9] I. Wästerlund, P. Nilsson, R. Gref, Influence of storage on properties of wood chip material, J. For. Sci. 63 (4) (2017) 182–191.

[10] E. Anerud, R. Jirjis, G. Larsson, L. Eliasson, Fuel quality of stored wood chips–Influence of semi-permeable covering material, Appl. Energy 231 (2018) 628–634.

[11] N. Hofmann, T. Mendel, F. Schulmeyer, D. Kuptz, H. Borchert, H. Hartmann, Drying effects and dry matter losses during seasonal storage of spruce wood chips under practical conditions, Biomass Bioenergy 111 (2018) 196–205.

[12] T. Thornqvist, The Importance of Cover and Air Underbase with Storage of Fuel Chips, Department of Forest Products, Swedish University of Agricultural Sciences, 1982.

[13] R. Spinelli, P. Kofman, N. Magagnotti, Wood chips stored under cover produce more heat, Inf. Agrar. 63 (5) (2007) 40–44.

[14] E. Anerud, J. Routa, D. Bergström, L. Eliasson, Fuel quality of stored spruce bark–Influence of semi-permeable covering material, Fuel 279 (2020) 118467.

[15] Anon, Solid Biofuels – Fuel Specifications and Classes –Part 1: General Requirements, SS-EN 14961-1:2010, Swedish Standard Institute, 2010.

[16] Anon, Solid Biofuels – Sampling SS-EN 14778, Swedish standards institute, 2011.

[17] Anon, Solid Biofuels – Sample Preparation. SS-EN 14780, Swedish standards institute, 2011.

[18] Anon, Solid Biofuels – Determination of Particle Size Distribution – Part 1: Oscillating Screen Method Using Sieve Apertures of 1 Mm and above SS-EN 15149-1, Swedish Standard Institute, 2010.

[19] Anon, Solid Biofuels – Determination of Moisture Content – Oven Dry Method – Part 1: Total Moisture – Reference Method. SS-EN 14774, Swedish standards institute, 2009.

[20] Anon, Solid Biofuels – Determination of Ash Content. SS-EN 14775, Swedish standards institute, 2009.

[21] Anon, Solid Biofuels – Determination of Calorific Value. SS-EN 14918, Swedish standards institute, Solid Biofuels, 2010.

[22] H. Gadd, S. Werner, Daily heat load variations in Swedish district heating systems, Appl. Energy 106 (2013) 47–55.

[23] S. Krigstin, S. Wetzel, A review of mechanisms responsible for changes to stored woody biomass fuels, Fuel 175 (2016) 75–86.

[24] H. Lenz, C. Idler, E. Hartung, R. Pecenka, Open-air storage of fine and coarse wood chips of poplar from short rotation coppice in covered piles, Biomass Bioenergy 83 (2015) 269–277.

[25] H. Lenz, R. Pecenka, C. Idler, S. Dumfort, C. Whittaker, C. Ammon, E. Hartung, Continuous weighing of a pile of poplar wood chips–A comparison of methods to determine the dry matter losses during storage, Biomass Bioenergy 96 (2017) 119–129.

[26] M. Manzone, P. Balsari, Poplar woodchip storage in small and medium piles with different forms, densities and volumes, Biomass Bioenergy 87 (2016) 162–168.

[27] R. Pecenka, H. Lenz, C. Idler, W. Daries, D. Ehlert, Development of bio-physical properties during storage of poplar chips from 15 ha test fields, Biomass Bioenergy 65 (2014) 13–19.

[28] M. Barontini, A. Scarfone, R. Spinelli, F. Gallucci, E. Santangelo, A. Acampora, R. Jirjis, V. Civitarese, L. Pari, Storage dynamics and fuel quality of poplar chips, Biomass Bioenergy 62 (2014) 17–25.

[29] T. Thörnqvist, Drying and storage of forest residues for energy production, Biomass 7 (2) (1985) 125–134.

[30] O. Bergman, T. Nilsson, Report on Outdoor Storage of Aspen-Wood Chips at the Hornefors Sulfite Mill. Ottawa (Canada), Canada Department of Fisheries and Forestry, 1971.

[31] H. Dahm, A comparison of log storage and chip storage of spruce, Norsk Skogindustri 20 (1) (1966) 10–&.

[32] C. Mitchell, J. Hudson, D. Gardner, P. Storry, A Comparative Study of Storage and Drying of Chips and Chunks in the UK, Production, Storage and Utilization of Wood Fuels, Proceeding of IEA/BA Conference Task III/Activity, 1988, pp. 72–89.

[33] T. Thörnqvist, G. Gustafsson, The Importance of Air Drying for the Storing Property of Fuel Chips, Report No. 142, Swedish University of Agricultural Sciences, Department of Forest Products Uppsala, 1983.

[34] O. Olsson, A. Eriksson, J. Sjöström, E. Anerud, Keep that fire burning: fuel supply risk management strategies of Swedish district heating plants and implications for energy security, Biomass Bioenergy 90 (2016) 70–77.