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Evaluation of an improved design for large-scale storage of wood chip and bark

Erik Anerud [a,*], Anders Eriksson [b]

[a] Department of Forest Biomaterials and Technology, Swedish University of Agricultural, Sweden
[b] Skogforsk, The Forestry Research Institute of Sweden, Uppsala Science Park, SE-75183, Uppsala, Sweden

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ABSTRACT

A developed bioeconomy needs better storage methods for wood chips and forest industry by-products, since increasing demands for more assortments, more storage will be necessary Today, solutions for coping with storage-related problems, such as dry matter losses and risk of self-ignition, are based on separating assortments into smaller piles and avoiding large-scale long-term storage of chips. A safe and efficient storage solution is needed to enable wood chip production all year round and not be limited to just-in-time production during the cold heating season when there is a large demand. This might result in a more robust system with larger buffer capacities, a less stressful working environment for chipping and transport contractors, and a better yearly machine utilisation.

This study evaluated storage outcomes for wood chips and bark when using an improved storage design that created assortment separation using concrete walls and a semipermeable sheet for cover. The new design enabled efficient area utilisation and increased fire safety. The storage outcome was also improved in terms of moisture content, dry matter losses and temperature development compared to conventional open-air piles.

1. Introduction

There is a need to replace fossil fuels with sustainable resources during the transition to a carbon negative society. In a future bioeconomy, an increased demand for renewable fuels and materials is expected. One way to meet this expected increased demand is to utilise more of the by-products and residue streams from the forest industry sector. In many countries, there is an untapped potential from woody residues produced by the forestry and forest industry i.e. materials not seen as a primary product but left to decompose instead. In the Nordic countries, utilisation of this residue stream has enabled the large heating sector to break its previous fossil fuel dependency [1].

If more woody residues are to be used in a future bioeconomy, better transportation and more storage are needed. Woody residues can be seen as a resource that is in the wrong place at the wrong time, so an efficient supply chain is needed to rectify this and unlock the full potential. In the heating sector, irregular seasonal demand leads to a challenging and stressful environment for the supply chain actors, since they need to scale production capacity up and down to cope with large variations in demand [2–4]. Just-in-time deliveries directly from the forest are common practice for primary residues with most material being chipped on demand. The forest industry generates by-products all year round which, when demand is low, need to be stored before being transported to end-users. This is a less-than-ideal situation, especially considering that fuel demand often changes at short notice as an effect of the outdoor temperature. It also adds cost, since extra personnel must be employed during the winter, yet in the summer, chipping equipment is underutilised. Large-scale storage of processed biomass can address these challenges, and the resulting increase in equipment utilisation offers the opportunity to reduce supply chain costs and thus improve the competitiveness of forest residues. However, large-scale storage at the heating plants is difficult due to their urban locations, with limited storage capacities ranging from a few days up to occasionally a few weeks' worth of fuel demand [5]. A way to address the seasonal factor and increase the supply chain robustness at the same time is to introduce large-scale storage of wood chips at terminals. This buffer in the system eases the situation for contractors as it allows for better and more robust utilisation of staff and machines. A terminal can also open up new markets and address the climate issue of truck transportation by introducing a change in transport mode e.g. from trucks to trains, which enables biomass residues to be transported from regions of surplus to those lacking them [6].

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

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Large-scale storage of wood chips is associated with a risk of degradation losses due to both biological and chemical processes, which ultimately can raise the temperature sufficiently to produce spontaneous self-ignition [7]. Chipped biomass offers a more favourable environment for microorganisms due to there being a larger exposed unprotected surface area to attack, easily available nutrients and the potential for an optimal temperature due to heat accumulation in compact and less well-ventilated storage piles. Monthly dry matter losses between 0.3 and 5.5% have been reported during storage of coniferous wood chips in uncovered piles [8–13]. According to Assarsson (1970), half of the losses that occur during the first months consist of low molecular carbohydrates, resins, acetic acid etc. [14]. In general, bark has a different chemical composition and physical structure compared to conifer wood chips. The proportion of parenchyma cells is higher in bark which results in more easily accessible sugars [15]. This gives rise to higher and longer respiration periods, and causes greater heat generation. In Sweden, dry matter losses around 5–10% after 2–5 months' storage time have been reported for bark [16–18].

Although storage might present new opportunities for the supply chain actors, it is also, as discussed, associated with material losses and a risk of self-ignition. Moreover, storage can both increase and decrease fuel quality and, thus, its value. This calls for smart storage management to take advantage of the benefits while, at the same time, controlling the negative effects. Recent studies have reported that natural drying can be facilitated by using a covering material to prevent rain and snow from rewetting the piles whilst enabling water vapour to ventilate the wood during storage. This also reduces the risk of dry matter losses [9,15,18].

At heating plants and terminals, pile height sometimes exceeds the maximum recommended due to lack of space. This increases natural compaction and prevents ventilation, allowing heat to build up in the piles, thus creating storage issues [13,19]. Materials with different combustion characteristics must be stored in separate piles to maintain product quality [20], so, as the piles at a terminal have to be separated with fire protective zones, the effective storage area reduces with increasing numbers of piles.

This study evaluated an improved storage management design for large-scale storage of wood chips at terminals, and its effect on the fuel characteristics and energy content during storage for six months. The design was based on separating the biomass into different compartments by using concrete walls, which created a physical barrier between different assortments, and covering the biomass with a semipermeable sheet. The idea was that this design addressed the frequently discussed challenges associated with large-scale wood chip storage such as safety, dry matter losses, quality changes and storage capacity. This storage design affects pile shape and limits the impact of wind during storage, potentially affecting storage outcomes.

2. Material and method

2.1. Material and storage location

The storage trial was carried out in Nykvarn, Sweden (59°10′N; 17°28′E), from February 2017 to August 2017. Wood chips produced from stored forest residues of Picea abies (L.) H. Karst and bark from Picea abies (L.) H. Karst were used in the storage trial. The comminution was performed in connection with the storage trial and chips and bark were transported by train to the storage site. Most of the chips (84% of four 10-L samples) were of a size in the range $8 \leq P \geq 45$ mm. The amount of fines <3.15 mm was 7.4%, thus classified as P45[a] according to SS-EN 149611 [21]. The bark was shredded with its main fraction within the size range $45 \leq P \geq 200$ mm.

2.2. Field trial structure and sampling

The experimental set-up consisted of two separate triangular shaped piles constructed against a concrete wall and two reference piles, i.e. piles constructed according to current practises in Sweden (Fig. 1a). The piles were constructed in February 2017 using a wheel loader. The dimensions of each reference pile, were 12.0 m (base) × 5.5 m (height) × 45.0 m (length), with an estimated volume of 1300 m^3 (ca. 400 Mg DM). The dimensions of the wood chip piles constructed against the wall were 6.0 m (base) x 5.5 m (height) x 40 m (length). The bark pile had the same 6.0 m base and 5.5 m height but was 55 m long. Thus, the estimated volume of the wood chip pile was 660 m^3 (ca.200 Mg DM) and the bark pile 900 m^3 (280 Mg DM). The piles were oriented with their long side perpendicular to the prevailing wind direction, which also maximised sun exposure of the piles during the storage period (Fig. 1a). During the experiment, one half of each pile (shown in grey in Fig. 1b.) was covered with a semipermeable material, Toptex®, with a specific weight of 200 g m^{-2}, and the other half was left uncovered as a control (Fig. 1b.). Within each half, four vertical sectors containing sample points (labelled with date in Fig. 1b.) were established for determination of moisture content (M, w.b.), ash content (A, d.b.), net calorific value, expressed at w.b, (Q) and dry matter loss (DML). During the construction of the piles, six samples were collected at each sampling point. Half of this sampled material was kept as a sub-sample of each sample, while the other half was placed into net bags (2.8 mm mesh size), weighed (0.01 g accuracy), and then returned to the sampling point. These net bags remained in the piles until final sampling and were collected from the exposed areas after storage and cleaned by removing any attached debris before being weighed. Each area within the piles constructed against the wall contained 18 samples and each area in the reference piles contained 27 samples. All samples were evenly distributed between the sampling points, as shown in Fig. 1c.

Tinytag ® temperature sensors and FireWorme® sensor cables, each with a sampling rate of 1 h, were used to monitor the temperature at 1.5–4.5 m height, sampling point 3, 7, 9 in the reference piles and sampling point 3, 5, 6 in piles constructed against the concreate wall (Fig. 1c), within the piles in the area labelled 2017–08. Sampling, sample preparation and analyses were carried out using standard methods (Table 1.) and the initial DM of the samples in the net bags was used as the basis for calculation of DML, which was expressed as mass loss (%) on a dry basis.

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

$$E_r = \frac{(1 - 0.01 * DML)}{(1 - 0.01 * M)} * Q \qquad \text{(Eq1)}$$

where E_r is recovered energy per initial mass, DML is dry matter loss as a relative proportion 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 180 SEK per MWh for wood chips and 150 SEK for bark, which corresponds to the average price for wood chips and bark in 2017 [27]. Conversions to EUR were made using the exchange rate in February 2017, giving a price of 18.9 EUR per MWh for wood chips and 15.8 EUR per MWh for bark.

2.3. Meteorological data for the storage site

Throughout the storage period, meteorological data including measurements of temperature and precipitation and historical data (30-year averages) for local weather conditions were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) weather station in Södertälje (59°12′N, 17°37′E), 10 km from the storage site. The mean ambient temperature during the pile construction in February 2017 was - 4.5 °C and the mean monthly temperature during storage was not significantly different from the average long-term value obtained from SMHI. The cumulative precipitation during the six-month storage period was 277 mm, which was 48 mm lower than the 30-year average for the region.

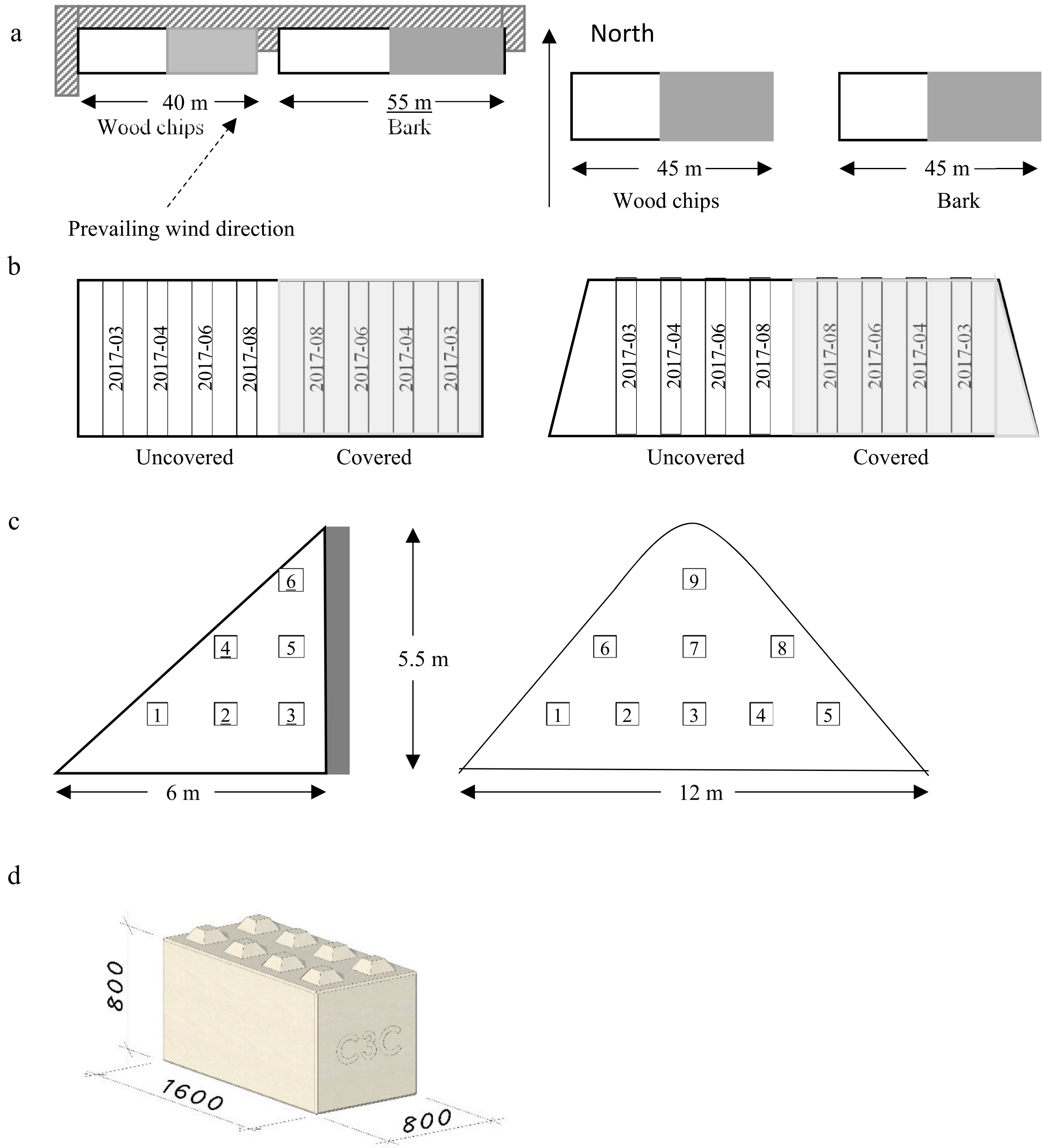

Fig. 1. a: Orientation of piles, showing the prevailing wind direction, b: sampling sections and sampling date, and c: cross-section of the experimental piles, showing sampling points. FireWorm® temperature sensors were placed at sampling points 3, 5 and 6 within piles constructed against the wall and at 3, 7, 9 within the reference piles. Tinytag ® temperature sensors were vertically placed at the same sampling points and d: concrete block used for the wall construction.

2.4. Statistical analysis

The experiment was treated as a randomised factorial experiment. Analysis of variance (ANOVA) was carried out using a general linear model (GLM) followed by Tukey's highly significant difference (HSD) test. The dependent variables (M, A, Q, DML, and E_r) were analysed with respect to the factors covered/not covered, pile form and storage duration. All analyses were carried out using STATISTICA v.10 and differences between factors and their interactions were considered significant at $P \leq 0.05$.

3. Results

3.1. Temperature development within piles

The temperature within all piles increased from 10 °C to above 40 °C within 24 h (Fig. 2). During the first 30 days of storage, the temperature in the uncovered reference wood chip pile peaked at 145 °C and the uncovered reference bark pile reached 104 °C. The wood chip pile constructed against a wall peaked at 99 °C and the bark pile at 85 °C. None on the covered piles exceeded 60 °C during the same period. In general, the temperature sum, i.e. the sum of daily average pile temperature, was higher when the material was stored following the reference method than against the wall. All covered piles had a lower

Table 1
Standards used for sampling, sample preparation, classification and determination of fuel characteristics.

	Standard	Reference
Sampling	SS-EN 14778	[22]
Sample preparation	SS-EN 14780	[23]
Fuel specifications and classes	SS-EN 149611:2010	[21]
Determination:		
Moisture content (M) expressed on a wet weight basis	SS-EN 14774: 2009	[24]
Ash content (A) expressed on a dry weight basis	SS-EN 14775:2009	[25]
Gross calorific value, expressed on a dry weight basis	SS-EN 14918:2010	[26]
Net calorific value (Q), expressed on a wet weight basis	SS-EN 14918:2010	[26]

temperature sum compared to uncovered piles. After 105 days of storage, the temperature sum for the reference piles reached 7958 °C (wood chips) and 7451 °C (bark). The obtained temperature sum for the material stored against a wall was 6784 °C for wood chips and 6300 °C for bark. The temperature sum in the covered reference piles was 5330 °C and the value when covered and placed against a wall was 4797 °C.

In general, precipitation affected the temperature of the uncovered piles, but not the covered piles. The result indicates that, in uncovered piles, precipitation triggers a temporary rise in temperature.

3.2. *Moisture content*

The initial moisture content (M, w.b.) during construction was 35.4% ± 3.9 (SD) in wood chips (n = 360) and 44.9% ± 4.6 (SD) in bark (n = 360). The average M in the uncovered wood chip piles increased to 40.7% during the first month, while there was no significant difference in the covered parts of the wood chip pile (Table 2.). Additional storage did not change the average M in any treatment for wood chips and the average M remained significantly higher in the uncovered reference compared to the other treatments. The average M in the covered bark pile constructed against the wall decreased significantly during the first month (Table 2.), while M in the other treatments did not change over the same period. Additional storage for four extra months resulted in significantly lower M in all treatments compared to the initial values, except for the uncovered reference.

3.3. *Ash content and calorific value*

The initial average ash content (A, d.b.) during the construction was 3.67% ± 0.07 (SD) in wood chips (n = 360) and 3.98% ± (SD) in bark (n = 360). The average A in uncovered wood chips increased significantly to 4.96% and the uncovered bark increased to 4.83% within the first month of storage, while A did not change when the biomass was covered. In general, the average A in the uncovered biomass did not increase after an additional storage for 5 months, except for the uncovered bark stored against the wall. However, when covered, the average A in wood chips increased to 5.12% and the average A in bark to 4.70% over the same storage duration. Despite a consistently higher average A in the uncovered piles, compared to the covered ones, no significant difference in average A occurred after storage. In terms of the A inside the piles, there was a positive correlation ($p < 0.05$, $R^2 = 0.56$) between A and temperature sum at the sampling point.

On average, the gross calorific value expressed on a dry basis ($q_{vgr, d}$) increased significantly ($p < 0.05$), regardless of storage method, from 21.09 $MJkg^{-1}$ to 21.37 $MJkg^{-1}$ in wood chips and from 20.27 $MJkg^{-1}$ to 20.61 $MJkg^{-1}$ in bark during the first month of storage. No further change in $q_{vgr, d}$ based on increased storage time, storage form or storage method was observed for wood chips. It is notable that the highest $q_{vgr, d}$ in wood chip piles was measured on samples taken from points where the temperature exceeded 150 °C. For the bark, the average $q_{vgr, d}$ was consistently higher in the uncovered piles than in the covered ones during storage, but it did not result in a significant difference. Additional storage for five extra months did not result in altered average $q_{vgr, d}$ except for the uncovered bark stored against the wall, where $q_{vgr, d}$ increased to 20.95 $MJkg^{-1}$. Storage of bark showed a positive correlation ($p < 0.05$, $R^2 = 0.43$) between the $q_{vgr, d}$ and the monitored temperature sum at the sampling points.

The average net calorific value (Q), expressed on a wet basis, of uncovered chip decreased during the first storage month from an

Table 2
Average moisture content (M, w.b.). Different letters within rows indicate significant differences between piles constructed with the same material and different Greek letters within columns indicate significant differences between storage durations.

	Date	Uncovered reference	Covered reference	Uncovered wall	Covered wall
Woodchips	2017-02-08	35.6aα	34.5aα	35.7aα	35.2aα
	2017-03-03	41.5aβ	34.4bα	39.8aβ	35.5bα
	2017-04-06	40.9aβ	35.5bcα	37.6baβ	34.1cα
	2017-06-13	40.5aβ	34.4bα	38.7 abαβ	36.3bα
	2017-08-17	40.6aβ	33.4bα	36.4baβ	33.1bα
Bark	2017-02-08	45.7aαβ	44.0aα	44.9aαβ	44.8aα
	2017-03-08	45.6aαβ	40.3baβ	46.2aα	40.2bβ
	2017-04-06	47.6aα	40.5baβ	41.5bβ	38.2bβ
	2017-06-13	41.0aγ	38.1 abβγ	33.8bcγ	29.4cγ
	2017-08-17	41.7aβγ	33.9bγ	32.9bcγ	28.5cγ

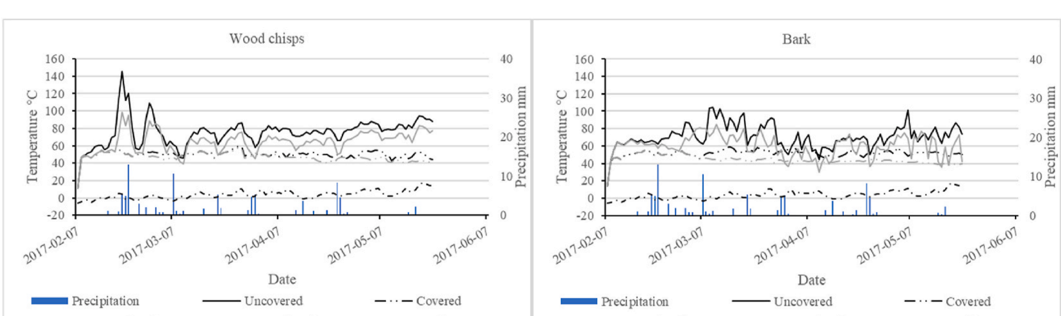

Fig. 2. Precipitation, ambient temperature and temperature changes within piles constructed of wood chips and bark.

average of 11.88 $MJkg^{-1}$ to 10.96 $MJkg^{-1}$ (Table 3.). No significant difference in average Q was determined during the same period in the covered wood chips piles. Additional storage of wood chips for five months increased Q compared to the values obtained after one month when stored against the wall, while Q in the reference piles did not change. The Q in the bark piles increased from an average of 9.36 $MJkg^{-1}$ to 10.54 $MJkg^{-1}$ when covered, and did not change in the uncovered piles during the first month of storage (Table 3.). Additional storage of bark for five extra months increased Q in all treatments, but showed significant differences between the uncovered reference pile and all other treatments (Table 3.).

3.4. Dry matter losses

The average dry matter loss (DML) after one month of storage reached 8.3% d.b in uncovered wood chips stored following common practice (Fig. 3.). The cumulative DML was significantly lower ($p < 0.05$) and reached 5.0% when uncovered wood chips were stored against the wall. At the sampling in March, there was a clear positive correlation ($p < 0.05$, $R^2 = 0.61$) between substance loss and moisture content, but also a positive correlation ($p < 0.05$, $R^2 = 0.56$) between substance loss and the temperature sum of the sampling point. Additional storage for five months reduced the difference between storage methods. The average cumulative DML reached 10.5% when wood chips were stored uncovered. The covered chips, irrespective of storage method, experienced significantly lower DML than the uncovered chips, an average 1.9% after one month of storage and 6.1% after addition storage for five months.

The uncovered bark showed an average DML of 5.9% after one month of storage, while the average DML in the covered bark was 3.1%. Only the difference between the covered and uncovered piles was significant. Additional storage for five months of uncovered bark following the reference method increased the average cumulative DML to 12.8%, while the increase, to 9.6%, was significant lower for the bark stored against the wall. During the same period, the average cumulative DML in covered bark increased to 6.6%.

3.5. Total accessible energy and economic value

The initial amount of accessible energy (E_r) derived from 1 kg initial dry material was 18.45.

MJ ± 0.05 (SD) (n = 360) in wood chips and 16.94 MJ ± 0.06 (SD) in bark (n = 360) (Fig. 4). In March, the E_r in uncovered wood chips had decreased significantly to 16.94 MJ (- 8.0%) when stored following the reference method and to 17.49 MJ (- 5.2%) when stored against the wall. The E_r in covered chips did not change significantly. Additional storage for five months resulted in a significant decrease in all treatments. The lowest average E_r obtained in the reference for uncovered wood chips was 16.51 MJ (- 10.5%), followed by the uncovered chips stored against the wall. The difference between those storage alternatives was significant ($p < 0.05$). The E_r in the covered chips decreased to an average of 17.67 MJ (- 4.2%), but it was still significantly higher than in the uncovered piles. The E_r in the uncovered bark reduced during the first month, regardless of storage form, to an average of 16.22 MJ (- 4.3%), while the covered bark did not change significantly. Additional storage for five months reduced the E_r to 15.61 MJ (- 7.9%) in the uncovered reference, while no other significant changes were statistically established.

When the biomass was stored following the uncovered reference method, the energy changes observed were equivalent to an economic loss during storage of 9.66 EUR/dry ton for wood chips and 4.91 EUR/dry ton for bark. The loss, when the same material was stored against a wall, was 7.12 EUR/dry ton for wood chips and 4.91 EUR/dry ton for bark. The use of cover reduced the loss to 3.5 EUR/dry ton wood chips regardless of storage method. For bark, the use of cover reduced the loss to 0.32 EUR/dry ton, while the combination of cover and storage against a wall increased the value to 2.32 EUR/dry ton.

4. Discussion

This study showed that a storage design using concrete compartments and a semipermeable covering resulted in significantly better storage outcomes in terms of quality, lower and more stable temperature development whilst helping fuel managers to keep assortments separate without unnecessary space between piles. Chips can therefore be stored in an effective and safer way. This is an interesting design and, if the improved storage design can be achieved at a cost lower than the net value improvements of the stored biomass, it is also directly profitable. Other parameters, such as area usage efficiency and assortment separation, also benefit from this design. The walls can also act as a foundation for a more mechanical and automated solution for rolling out the covering fabric. Different timescales and depreciation will affect the cost calculations, and it is clear that concrete walls are a more long-term solution compared to semipermeable fabrics, although these have been shown to withstand several reuses during previous storage trials.

This study has shown that separation of different assortments in concrete compartments can be achieved without risking deleterious storage outcomes compared to a conventional open storage pile. A storage solution using concrete compartments addresses current challenges in keeping assortments separated in narrow terminals but avoids quality reduction and self-ignition. Moreover, the legally required minimum fire protection distance can be reduced which increases storage capacity.

The temperature within piles are a reflection of biological and chemical activity, which combined leads to DML during storage. The activity is affected by material properties, e.g. access to easily degradable nutrients, chemical composition and moisture content, but also particle size distribution, compaction, permeability, volume and stack height, since this affect the airflow and heat transfer dynamics within piles. Storage against a wall require less volume per m height and in

Table 3
Average ash content (A), % d.b and net calorific value (Q) $MJkg^{-1}$. Different letters within rows indicate significant differences between piles constructed with the same material and different Greek letters within columns indicate significant differences between storage durations.

	Date	Uncovered reference		Covered reference		Uncovered wall		Covered wall	
		A	Q	A	Q	A	Q	A	Q
Woodchips	2017-02-08	3.54aα	11.89aα	3.64aα	12.15aα	3.69aα	11.86aα	3.86aα	11.96aα
	2017-03-03	4.73aβ	10.82aβ	4.21 abα	12.28bα	5.19aβ	11.09aβ	3.57bα	12.02bα
	2017-04-06	4.34aαβ	10.95aβ	4.22aα	12.31bα	5.19aβ	11.58aαβ	4.05aα	12.32αβ
	2017-06-13	4.93aβ	11.06aβ	4.10aα	12.07bα	5.12aβ	11.42aαβ	4.14aα	11.98bα
	2017-08-17	5.67aβ	11.03aβ	4.57aα	12.57bα	4.48aβ	11.99bα	5.67aβ	12.55bβ
Bark	2017-02-08	3.92aα	9.17aα	3.99aα	9.52aα	4.00aα	9.35aα	4.01aα	9.38aα
	2017-03-08	4.97aβ	9.43aα	4.10aα	10.58bβ	4.69aβ	9.24aα	4.19aα	10.50bβ
	2017-04-06	5.14aβ	9.02aα	4.34aα	10.42bβ	4.55aβ	10.38bβ	4.61aαβ	10.93bβ
	2017-06-13	5.11aβ	10.54aβ	5.22aβ	10.95aβγ	5.36aγ	12.01bγ	4.71aαβ	12.90bγ
	2017-08-17	5.38aβ	10.43aβ	4.80aαβ	12.04bγ	5.34aγ	12.23bγ	4.60aαβ	13.16bγ

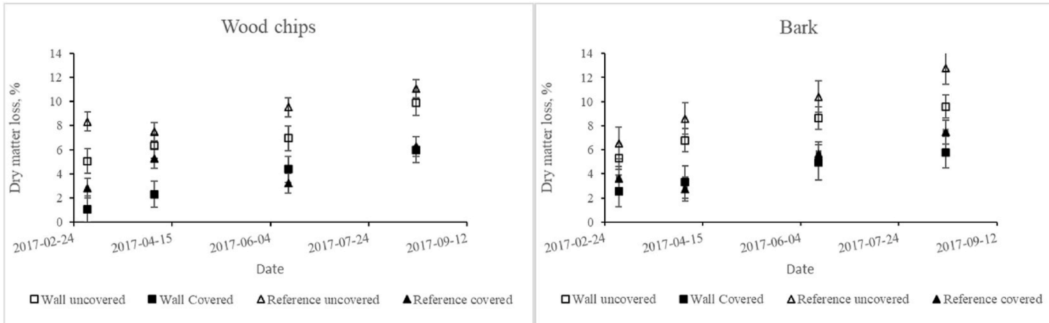

Fig. 3. Average dry matter losses during storage and 95% level of confidence.

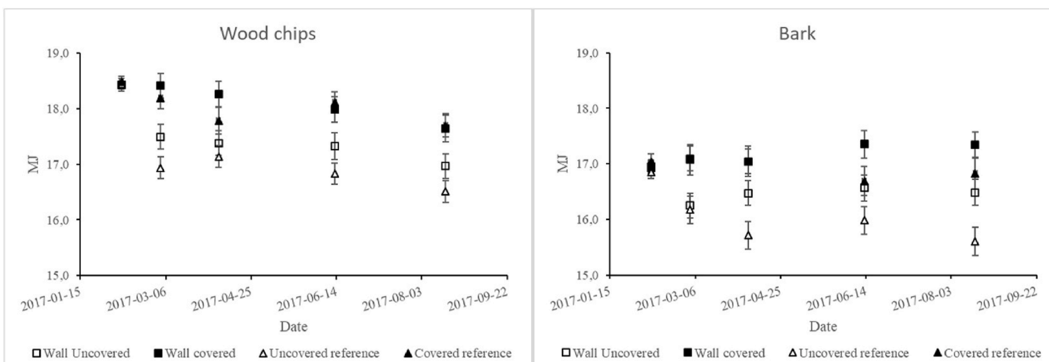

Fig. 4. Energy available after storage, expressed as recovered energy per initial mass of 1 kg dry matter and 95% level of confidence.

addition, the wall shields wind from one direction and thus affect the airflow and heat transfer dynamics. Our results showed that storage against a wall led to lower activity, i.e. lower temperature when biomass was stored uncovered.

The moisture content of biomass is the most important parameter during storage since it affects fuel quality, in particular, the net calorific value, and biological activity which causes DML. Therefore, methods that facilitate natural drying is essential. High temperature within pile reduce M, however, biomass, which is a hygroscopic material, is exposed to precipitation and can easily be rewetted during storage. Covering the chips with a semipermeable fabric led to considerably lower temperatures within the pile compared to the uncovered reference, irrespective of the material studied. The covered piles also showed more stable behaviour without the temperature increases triggered by heavy precipitation which were seen in the reference piles. Moreover, the rewetting process seen during the first month in the uncovered wood chip piles could be avoided if the piles were covered, thus resulting in dryer material after storage. The covered bark piles resulted in dryer material compared to the uncovered reference pile. This is in line with previous studies [9,10,18,28–30].

The combined effect of treatment on E_r was calculated on individual samples and DML and the variations in parameters M and Q were captured within the calculated value. Our result showed that piles constructed according to current practise is worse than storing against a wall if not covered. However, covering was the best option. This result is explained by a combination of DML and changes in M due to natural drying and rewetting.

A future bioeconomy, which includes increased collection of residues and usage of biomass waste as feedstock or as input to value-creating processes, will require more storage as a method to bridge the gap between continuous residue streams and fluctuating demand. Long-term storage between seasons is associated with risks such as material degradation, quality deterioration and self-ignition. These risks are currently addressed by avoiding storage of unprocessed material when possible. When processed chips must be stored, they are stored in small separate piles over short periods. When striving for efficiency and an increased competitiveness to other fuels, the current methods for dealing with storage risks are not necessarily the best. Recommendations and requirements such as a maximum height of piles, a minimum distance between piles, and separation of different assortments, tend to be ignored when more biomass is squeezed into narrow terminal areas, resulting in avoidable material losses and, ultimately, terminal fires [20]. Both terminals and end-users face these expected problems and these issues are the main motivation for the storage solution presented here.

Moreover, the tight profit margins that supply chain actors and contractors work with require supply chain efficiency improvements to remain competitive. Current just-in-time deliveries of processed material mean that chipping and transportation must be carried out over a few winter months to meet the demand from the heating sector. If comminution of the material occurred over the whole year, and if the material was stored at terminals near the end-user, then the chipping contractor could use their machinery for more hours during the year, thus ease the stressful winter situation. Terminal storage can also cut costs and facilitate better yearly planning of biomass supply if more products can be handled in favourable conditions e.g. summer handling of objects with limited possibilities to coordinate e.g. snow ploughing with other forest activities.

A practical learnings from a previous incident at a terminal supports the idea that the concrete wall can withstand self-ignited fires and limit the fire's spread. By acting as a physical barrier, other biomass assortments were protected. Such learnings, in addition to the field trial, support the claim that the area usage efficiency is increased, as material can be stored all the way to the outer edge of the terminal. Separating assortments with a wall instead of being placed at a distance from each other also contributes to increased area usage efficiency, especially if there are many different assortments and fuels being stored. It is likely that the number of assortments will increase in a future bioeconomy where forest biomass is used as the raw material for a wider range of products in new and developed industry applications. The trends in value creation, productification and tailored deliveries of certain qualities also advocate a wall solution [31]. However, the benefits must be related to the extra cost of installing the wall at a terminal.

This study has shown that a solution with concrete walls in combination with a semipermeable covering material results in a better storage outcome for two different assortments. However, more studies are needed to prove that these results are valid under different conditions, and for other assortments. In this study design, the piles were built against only one side of the wall, leaving the other exposed to the wind. The effect of stacking chips against both sides of the wall must be addressed in future studies. When considering the same pile height, but only against one wall, only half of the potential volume of material was stored which might also influence the applicability of the results.

5. Conclusion

This study has shown that wood chips can be stored in large-scale concrete compartments without resulting in poorer storage outcomes in terms of moisture content, dry matter losses and temperature development compared to conventional open-air piles. At the same time, the compartments can facilitate an efficient use of space and improve fire safety. An improved storage design with both concrete walls and a semipermeable covering material resulted in better storage outcomes compared to the reference method.

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References

[1] S. Werner, District heating and cooling in Sweden, Energy 126 (2017) 419–429.
[2] 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.
[3] 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.
[4] 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.
[5] 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.
[6] K. Väätäinen, P. Anttila, L. Eliasson, J. Enström, J. Laitila, R. Prinz, J. Routa, Roundwood and biomass logistics in Finland and Sweden, Croatian journal of forest engineering, Journal for Theory and Application of Forestry Engineering 42 (1) (2021) 39–61.
[7] S. Krigstin, S. Wetzel, A review of mechanisms responsible for changes to stored woody biomass fuels, Fuel 175 (2016) 75–86.
[8] E. Anerud, G. Larsson, L. Eliasson, Storage of wood chips: effect of chip size on storage properties, Croat. J. For. Eng.: Journal for Theory and Application of Forestry Engineering 41 (2) (2020) 1–11.
[9] 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.
[10] 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.
[11] P. Jylhä, J. Hytönen, J. Alm, CO2 release and dry matter loss of Scots pine forest chips stockpiled from late summer to winter, Biomass Bioenergy 104 (2017) 36–44.
[12] I. Wästerlund, P. Nilsson, R. Gref, Influence of storage on properties of wood chip material, J. FOR. SCI 63 (4) (2017) 182–191.
[13] T. Thörnqvist, Drying and storage of forest residues for energy production, Biomass 7 (2) (1985) 125–134.
[14] A. Assarsson, I. Croon, E. Frisk, Outside chip storage (OCS), 16; 17, Sven. Papperstidning 73 (1970) 493, 41.
[15] 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.
[16] R. Fredholm, R. Jirjis, Säsongslagring av bark från våtlagrade stockar=, Sveriges lantbruksuniversitet, Institutionen för virkeslara1988.
[17] R. Jirjis Lehtikangas, Storage of Wood Chips and Bark in Northern Sweden, Rapport-Institutionen För Virkeslära, Sveriges Lantbruksuniversitet, Uppsala, Sweden, 1998.
[18] E. Anerud, J. Routa, D. Bergström, L. Eliasson, Fuel quality of stored spruce bark–Influence of semi-permeable covering material, Fuel 279 (2020) 118467.
[19] R. Jirjis, Storage and drying of wood fuel, Biomass Bioenergy 9 (1–5) (1995) 181–190.
[20] P. Lehtikangas, Lagringshandbok För Trädbränslen, Sveriges lantbruksuniv, 1998.
[21] Anon, Solid Biofuels – Fuel Specifications and Classes –Part 1: General Requirements, SS-EN 14961-1:2010, Swedish Standard Institute, 2010.
[22] Anon, Solid Biofuels – Sampling SS-EN 14778, Swedish standards institute, 2011.
[23] Anon, Solid Biofuels – Sample Preparation. SS-EN 14780, Swedish standards institute, 2011.
[24] Anon, Solid Biofuels – Determination of Moisture Content – Oven Dry Method – Part 1: Total Moisture – Reference Method. SS-EN 14774, Swedish standards institute, 2009.
[25] Anon, Solid Biofuels – Determination of Ash Content. SS-EN 14775, Swedish standards institute, 2009.
[26] Anon, Solid Biofuels – Determination of Calorific Value. SS-EN 14918, Swedish standards institute, Solid Biofuels, 2010.
[27] Wood Fuel- and Peat Prices, 2018.
[28] M. Manzone, P. Balsari, R. Spinelli, Small-scale storage techniques for fuel chips from short rotation forestry, Fuel 109 (2013) 687–692.
[29] 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.
[30] S. Wetzel, S. Volpe, J. Damianopoulos, S. Krigstin, Can biomass quality Be preserved through tarping comminuted roadside biomass piles? Forests 8 (9) (2017) 305.
[31] A. Eriksson, Improving the Efficiency of Forest Fuel Supply Chains, 2016.