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Sieving and Covering of Wood Chips Improves Storability

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Abstract: Minimising dry matter losses during storage of comminuted forest fuels is desirable from both an economic and a sustainability perspective. This study examined fuel quality and amount of recovered energy during the storage of forest wood chips stored at full industrial scale at three locations, and the effect of sieving and covering piles with a water-resistant, vapour-permeable fabric. Sieving wood chips before storage, that is, reducing the number of fines smaller than 8 mm, reduced the cumulative dry matter losses to <2%, while cumulative dry matter losses after storage for 4–6 months using current practices, that is, unsieved and uncovered, reached 10.6%. The combined effect of storage management led to a value loss of 11.5%, while both covering and sieving led to lower losses, with the combination of sieving and covering giving a 1.3% value increase, and thus, increased storability.

Keywords: dry matter loss; forest fuel; fuel quality; moisture content

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1. Introduction

The use of forest residues and forest industry byproducts for heat and power generation has substantially contributed to the developing transition to a fossil fuel-free society in Sweden and Finland. Storage of solid biofuels intended for heat and power is an essential step within the supply chain to secure the supply of fuels, as there is an irregular seasonal demand for energy [1]. Both logistic and economic considerations influence storage methods and location within the supply chain. On the one hand, transport and comminution affect supply chain costs [2,3], but the uneven demand leads to inefficient equipment utilisation. On the other hand, more efficient equipment use increases storage capacity requirements for comminuted fuels.

In general, forest residues (LR) dry during storage [4–6], leading to lower moisture content (M), and increased net calorific value (Q). This is valid also for compacted residues [7,8]. Drying of stacked residues can be improved if the stacks are covered [4,9,10]. Storage of comminuted LR is associated with increased risks for extensive dry matter loss (DML) due to the degradation of biomass and spontaneous ignition caused by biological and chemical processes leading to self-heating [11]. DML of around 1–4% per month has been reported for comminuted LR of coniferous species [12–14] in Sweden and Finland. Similar DML rates were found in our earlier large-scale trials of coniferous fuel chips [15–17]. Their DML is similar to the result for coniferous wood chips stored in Germany [18], but not for poplar chips [19,20]. Poplar also has high rates of dry matter loss in Italian studies [21–23]. Dry matter losses seem to be generally higher for the storage of deciduous wood chips [24–26]. Initial fuel properties, such as M, readily available nutrients, particle size distribution and chip size and storage conditions such as pile properties (pile height, pile shape and degree of compaction) all affect the biological activity in storage piles [12]. The biomass, M, directly affects the conditions for biological degradation during storage [27], so methods that accelerate the natural drying process are highly desirable. The activity within piles that leads to dry matter losses can be reduced by using a semi-permeable cover that protects the fuel against rewetting and, at the same time, allows for heat transfer and water vapour dissipation to the atmosphere [14,16,28]. The degradation process can also be reduced by increasing the target chip size in the chippers; sieving off fine particles results in significantly lower DML [21,29,30].

The objective of this study was to evaluate sieving and covering as methods to increase the storability of wood fuel chips, regarding fuel quality, DML, and energy content, during full-scale long-term storage under industrial conditions.

2. Materials and Methods

2.1. Material and Storage Locations

Storage trials were carried out at three terminals (blocks) in Sweden: Norrsundet (60°56′ N; 17°9′ E) (block 1), Älvsbyn (65°40′ N; 20°58′ E) (block 2) and Mora (60°58′ N; 14°31′ E) (block 3). The trial was carried out from September 2019 to February 2020 in block 1, from May 2020 to August 2020 in block 2 and from May 2020 to August 2020 in block 3. Wood chips, produced from stored LR from cuttings of predominantly Norway spruce (*Picea abies* (L.) H. Karst), were used at all blocks. In block 1 and block 3, comminution was coordinated with the construction of storage piles; in block 2, residues were comminuted before the field trial and thus were pre-stored. The main size fraction of the stored chips was in the range 3.15 mm to 45 mm and the distribution of fines (<3.15 mm) varied (Figure 1).

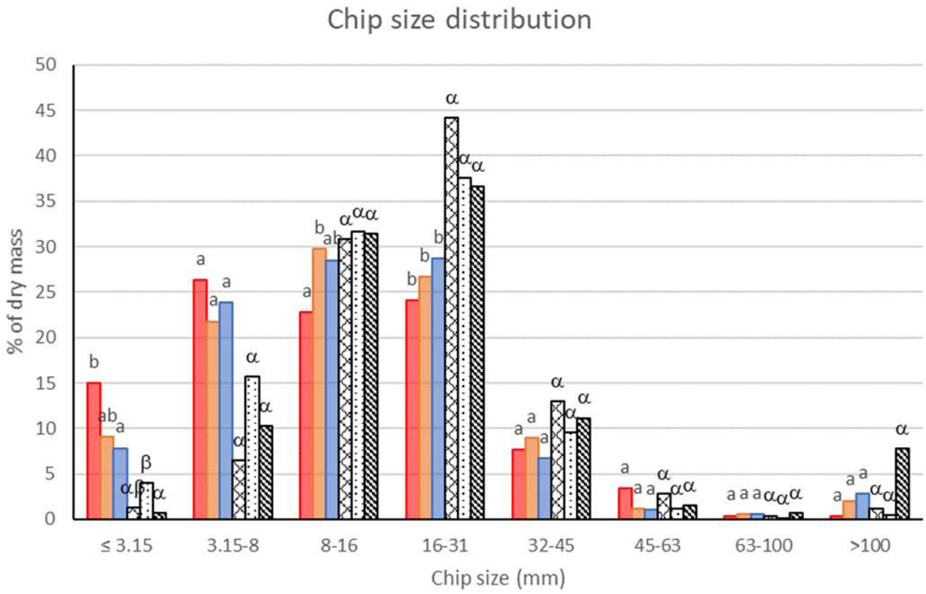

Figure 1. Particle size distribution for unsieved and sieved woodchips from the three study sites. Coloured bars beneath different Roman letters indicate a significant difference in the material as delivered between study sites. Different Greek letters centred in the patterned bars indicate a significant difference in the sieved material between study sites. Block 1 is represented by red and cross-hatched bars, block 2 by orange and dotted bars and block 3 by blue and diagonally striped bars.

The chips were produced with a chipper and then screened into different qualities using Backers star screens (Backers, Twist, Germany) in block 1 and block 3 and a Maskin Mekano Lv 302 T3 vibrating screen (Maskin Mekano, Jönköping, Sweden) in block 2. Fines were separated using sieving decks that separated 8 mm grain size in block 3 and 8 mm and 10 mm in block 1. In block 2, a 15 × 15 mm mesh size screen was used. The sieving operation took place on the same days as the establishment of the storage trials; sieving performance is described in [31]. The sieving operation reduced the variations in chip size distribution, and significant differences between study sites could only be found for the fines. Chip size distributions were analysed with a generalised linear model (GLIMMIX) in SAS using a logit link function on chip size proportions (S) using the factors' Site' and 'Chip size class' (Equation (1)). The use of the logit link is necessary since it transforms the primary range of proportions (S) from the interval [0,1] into the interval [–∞, ∞], assuming normal distribution. The test criteria are the interaction of 'Chip size class' with 'Site location' (Site Location × Chip size class) and so, if the effect of 'Chip size class' is found to be independent of the interactive factor 'Site location', it can be assumed that site does not affect chip size distribution [32].

$$\text{Logit S} = \text{Study site} + \text{Chip size\_class} + \text{Study site} \times \text{Chip size\_class} + \varepsilon. \quad (1)$$

2.2. Field Trial Structure and Sampling

The experimental setup consisted of three blocks (locations) and four treatments: unsieved/sieved and uncovered/covered. Two separate triangular-shaped piles were constructed with wheel loaders at each block on paved surfaces, one with sieved chips and one with unsieved. The pile height (5.5 m) and base (12.0 m) were identical at each location, but the length varied. The total volume of each pile (Table 1) was calculated with photogrammetry (Agrifoft Metashape, Agisoft LCC, St. Petersburg, Russia) from pictures taken with a drone (DJI Mavic 2 pro). The estimated pile volumes were confirmed by reference measurement of objects with known volumes to a precision better than 99.9% and an accuracy of 0.1 m^3.

Table 1. Initial volume (m^3) of wood chip piles.

Location/Block	Unsieved Wood Chips	Sieved Wood Chips
Block 1	618	781
Block 2	975	1100
Block 3	1185	1315

The piles were oriented with their longest side perpendicular to the prevailing wind direction, which also maximised sun exposure of the piles over the storage period (Figure 2a). During the experiment, one half of each pile (shown in grey in Figure 2b) was covered with a semi-permeable material, Toptex®, with a specific weight of 200 g m^{-2}, while the other half was left uncovered as a control (Figure 2b). Each half was divided into three vertical sectors (Figure 2b) containing sample points (Figure 2c). During the construction of the stacks, a general sample (10 L) was collected at each sampling point. Half of this sampled material was saved for further analysis of the initial characteristics of wood chips, while the other half was placed into net bags (2.8 mm mesh size), weighed (0.0 g accuracy), and then returned to the stacks. All samples were evenly distributed between the sampling points, with an approximate distance of 1.5 m between sampling bags, as shown in Figure 2c. Each zone within the piles contained nine samples. The temperature within piles in sectors, labelled Sampling 3 (Figure 2b), was monitored using TinyTags (TGP-4500, intab, Stenkullen, Sweden) with a sampling rate of 1 h at 3.0 m and 4.5 m height, at sampling points 7 and 9 respectively (Figure 2c).

Initial and changed fuel characteristics, based on M (% w.b), gross calorific value ($MJkg^{-1,}$ d.b), net calorific value ($MJkg^{-1}$ w.b, Q) and particle size distribution, were determined using standard procedures (Table 2). At the same time, DML expressed as mass loss (%) on a dry weight basis was calculated from the net bag samples. During resampling, samples from exposed sections (Figure 2b) were collected as shown in Figure 2d, and the section was immediately restored.

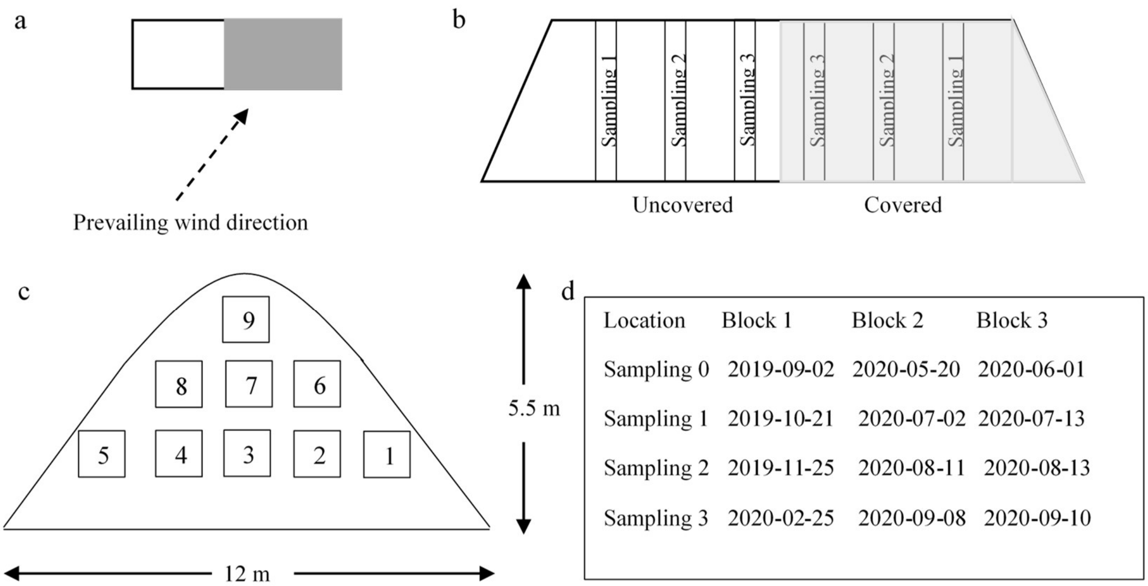

Figure 2. (**a**): Orientation of stacks, showing the prevailing wind direction, (**b**): sampling sections and order of resampling and (**c**): cross-section of the experimental stacks, showing sampling points. TinyTags ® temperature sensors were placed at sampling points 7 and 9, (**d**): sampling time.

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

	Standard	Reference
Particle size distribution	SS-EN 15149-1: 2010	[33]
Moisture content (M) expressed on a wet weight basis	SS-EN 14774: 2009	[34]
Gross and net calorific value, expressed on a dry weight and wet weight basis respectively	SS-EN 14918: 2010	[35]

The determined M, Q and DML were used to calculate available energy, expressed as recovered energy (E_r). The E_r was calculated as:

$$E_r = \frac{(1 - 0.01\ \mathrm{DML})}{(1 - 0.01\ \mathrm{M})} * Q \quad (2)$$

where E_r is recovered energy per initial mass, DML is defined as the relative proportion of initial mass, M is moisture content on a wet weight basis and Q is net calorific value on a wet basis. Thus, the effect of storage on E_r can be calculated as the difference between E_r after storage divided by E_r before storage.

2.3. Meteorological Data for the Storage Sites

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 nearby Swedish Meteorological and Hydrological Institute (SMHI) weather stations at Gävle (60°42′ N; 17°9′ E), Älvsbyn (65°40′ N; 21°3′ E) and Mora (60°57′ N; 14°30′ E).

In general, differences between the monitored average monthly ambient temperature and the 30 year average value obtained from SMHI were small, except during December to February in block 1, where the ambient temperature was 5–7 °C higher than the average (Figure 3a). The cumulative precipitation during the storage trials was 310 mm, 315 mm and 235 mm in blocks 1–3, respectively, which corresponds to a difference of 16%, 22% and

−17% compared to the average amount of precipitation (Figure 3b). Higher than average levels of precipitation occurred during July (between samplings 1–3) in block 2 (+141%) and block 3 (+56%), and in October for block 1 between samplings 1 and 2 (+163%) (Figure 3b).

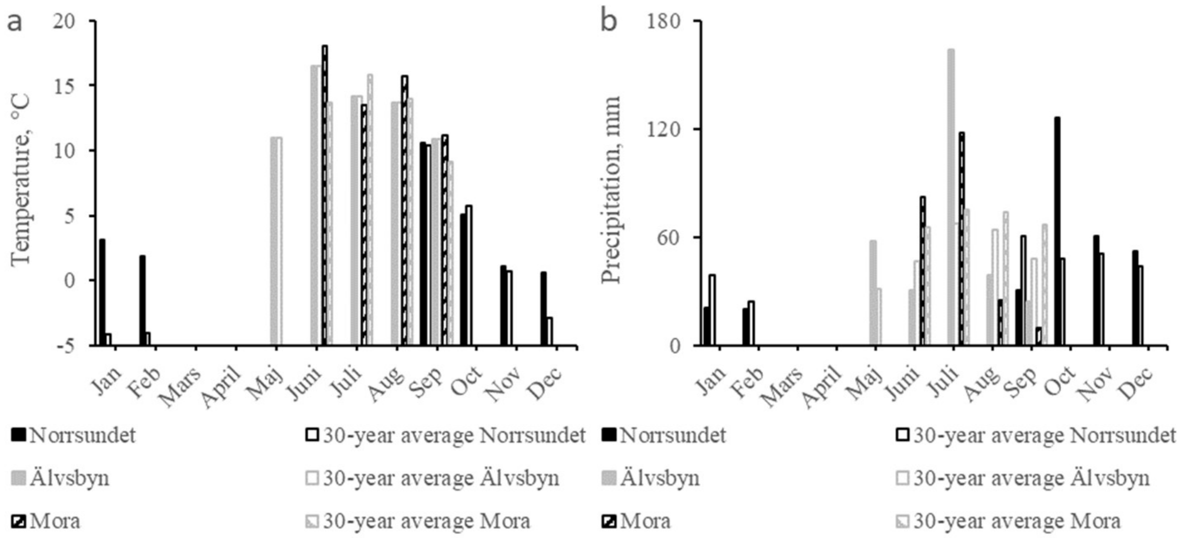

Figure 3. (**a**): Monthly ambient temperature during the storage trials and 30-year average ambient temperature obtained from SMHI, and (**b**): monthly cumulative precipitation during the storage trials and 30-year average precipitation obtained from SMHI.

2.4. Statistical Analysis

The experiment was designed 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, Q, DML and recovered energy) were analysed for each factor: block, sieved/unsieved, covered/uncovered and storage duration. All analyses were carried out using STATISTICA v.10 (StatSoft, Hamburg, Germany), and differences between factors and interactions were considered significant at $p \leq 0.05$.

3. Results

3.1. Temperature Development within Piles

The average temperature within all piles increased from ambient to above 40 °C within the first seven days of storage. After that, the storage conditions for the different treatments led to significant differences in temperature development (Figure 4). In general, the average temperature in sieved piles did not exceed 40 °C after 14 days of storage, while the average temperature was significantly higher in unsieved piles. These differences persisted over the whole storage period. There was also a clear difference in temperature between uncovered and covered material, except for sieved chips stored in block 3. In addition, the temperature at 4.5 m increased linked to precipitation when stored following the reference method.

After 30 days of storage, the cumulative sum of the daily average temperature (Tsum) in the uncovered reference piles reached 1868 °C in block 1 and 1718 °C in block 3. During the same period, the Tsum in sieved and covered wood chips reached 411 °C in block 1 and 930 °C in block 3. At the end of the storage trial, the Tsum in chip piles, stored following the reference method, reached 10,162 °C in block 1 and 5698 °C in block 3, while during the same period, the Tsum in sieved and covered material reached 829 °C in block 1 and 2155 °C in block 3. Notably, the temperature at 3.0 m and 4.5 m heights was periodically below 0 °C in the sieved and covered material stored at the terminal in block 1.

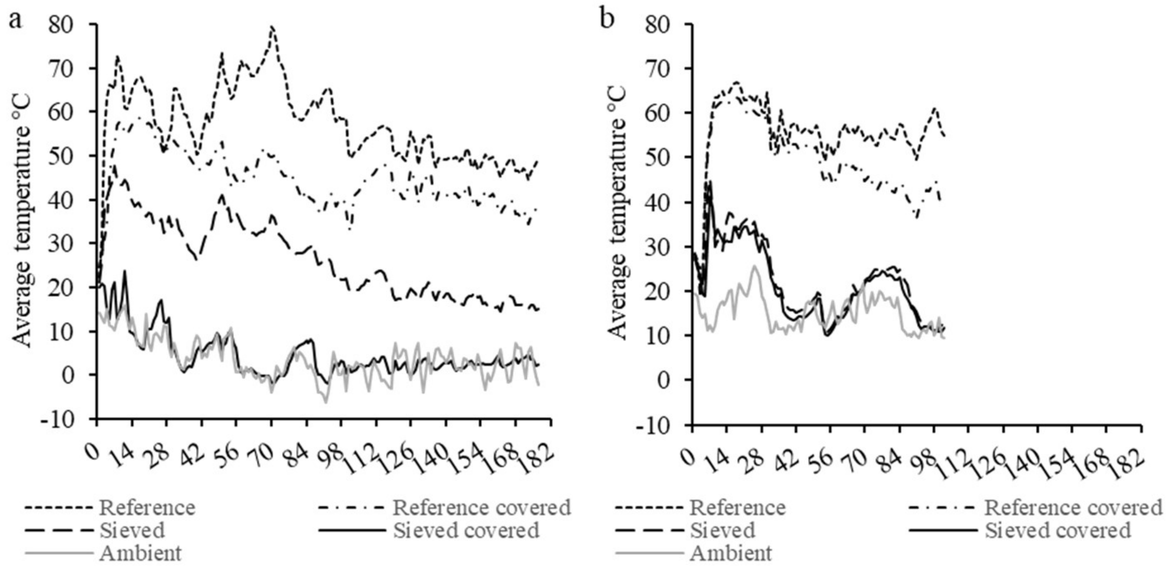

Figure 4. The average temperature during storage of wood chips in block 1 (**a**) and block 3 (**b**).

3.2. Moisture Content (M)

Sieving of the produced chips entailed homogenisation and reduced the initial M from 44.73% ± 5.54 (SD) to 33.42% ± 3.64 (SD), and from 44.05% ± 9.56 (SD) to 26.59% ± 3.91 (SD) in block 1 and block 2, respectively. However, sieving of the pre-stored chips in block 2, where the initial M of unsieved chips was 39.25% ± 2.74 (SD), did not affect the initial M of 40.22 ± 3.17 (SD) in sieved chips. The effect of blocks showed a significant (p < 0.01) effect on the difference (D) between initial M and M after storage (Table 3). The average M decreased in all treatments during the first 42–49 days of storage, except in block 1, where uncovered piles were rewetted by precipitation and reached 58.9% at sampling point 9. The uncovered chips showed lower D than covered, irrespective of whether they had been sieved or not. With an additional cover, the unsieved showed greater D than the sieved.

Table 3. ANOVA table for the difference in Moisture content (w.b) during storage of wood chips.

Effect	Df	Sum Sq (SS)	Mean Sq (MS)	F-value	p-Value
Intercept	1	16,331	16,331	369	0.000
Block	2	1857	928	21	0.000
Sieved	1	2642	2642	60	0.000
Covered	1	237	237	5	0.021
Block *Sieved	2	729	364	8	0.000
Block *Covered	2	658	329	7	0.001
Sieved*Covered	1	250	250	6	0.018
Block *Sieved*Covered	2	33	17	0	0.687
Error	288	12,740	44		

At resampling event 2, after 73–84 days of storage, there was an 8% difference in average M between unsieved and sieved piles. The M in uncovered reference piles increased during the rainy period in July (Figure 2b), while the M in covered piles decreased (Figure 5). Additional storage neither increased the average M in unsieved piles nor decreased the average M in sieved piles within the treatment.

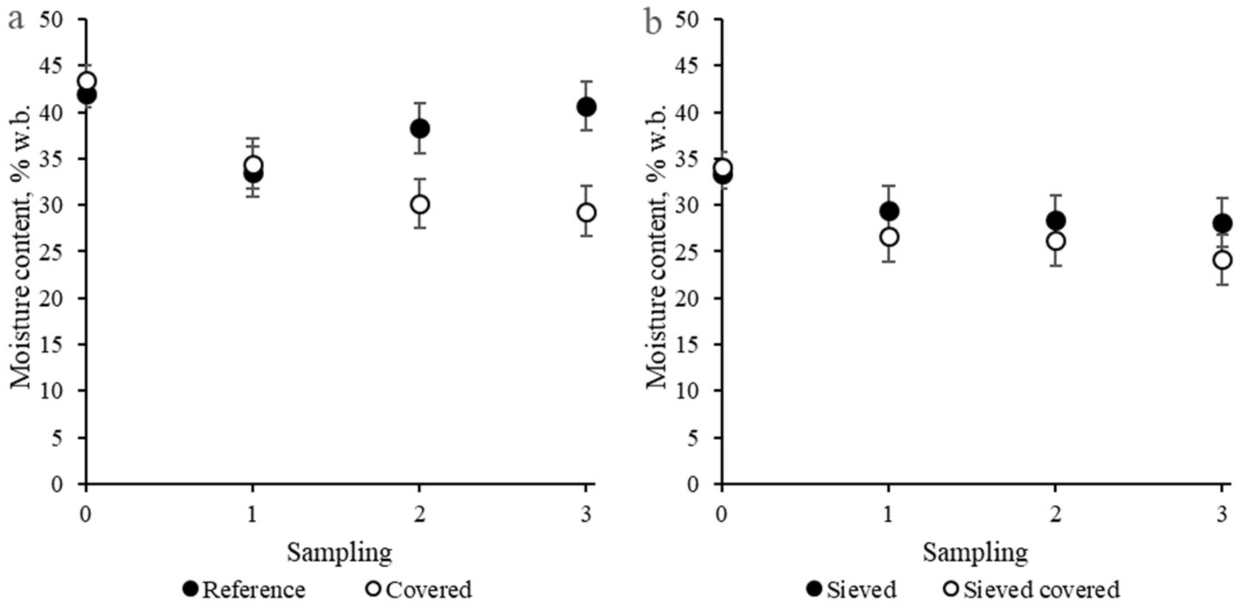

Figure 5. Mean moisture content (%, w.b.) and 95% level of confidence intervals of unsieved (**a**) and sieved (**b**) wood chips during storage.

3.3. Dry Matter Loss (DML)

There was a significant ($p < 0.01$) block effect on DML and, in general, the DML of pre-stored chips was higher in block 2 compared to the other locations. However, all blocks showed the same significant ($p < 0.01$) pattern between treatments. Storage of sieved wood chips in uncovered piles for 42–47 days resulted in an average DML of 1.22% ± 0.51 SD when stored in uncovered piles, while the average DML in piles stored according to the reference method was 5.37% ± 1.19 SD (Table 4). Further storage increased the difference between the uncovered treatments which, at the end of the storage trial, resulted in a cumulative DML of 1.47% ± 0.80 SD and 10.63% ± 1.99 SD for sieved and unsieved chips, respectively. In general, the additional use of a cover led to lower DML during storage, but the effect of covering on DML was only significant ($p < 0.01$) for unsieved chips.

Table 4. Average cumulative dry matter loss, as %, during storage. Different letters within rows indicate significant differences between storage duration, and different Greek letters in columns indicate significant differences between treatments.

Treatment	**Sampling 1 (42–49 Days)**	**Sampling 2 (73–84 Days)**	**Sampling 3 (101–176 Days)**
Uncovered	5.37aα	6.52bα	10.63cα
Covered	3.64aβ	4.84bβ	5.88cβ
Sieved uncovered	1.22aγ	1.40aγ	1.47aγ
Sieved covered	0.75aγ	0.97aγ	1.18aγ

3.4. Net Calorific Value (Q) and Recovered Energy per Initial Mass (E_r)

The initial average net calorific value (Q), expressed on a wet weight basis of unsieved chips, was 9.73 MJ kg^{-1} ± 1.79 SD with sieving significantly ($p < 0.01$) increasing the initial average Q to 12.03 MJ kg^{-1} ± 1.49 SD (Figure 5). In general, the average Q increased, but the increase was only significant ($p < 0.01$) in covered piles where it increased to 12.73 MJ kg^{-1} ± 1.17 SD (23.6%) and 14.03 MJ kg^{-1} ± 0.67 (16.6%) in unsieved and sieved piles, respectively (Figure 6).

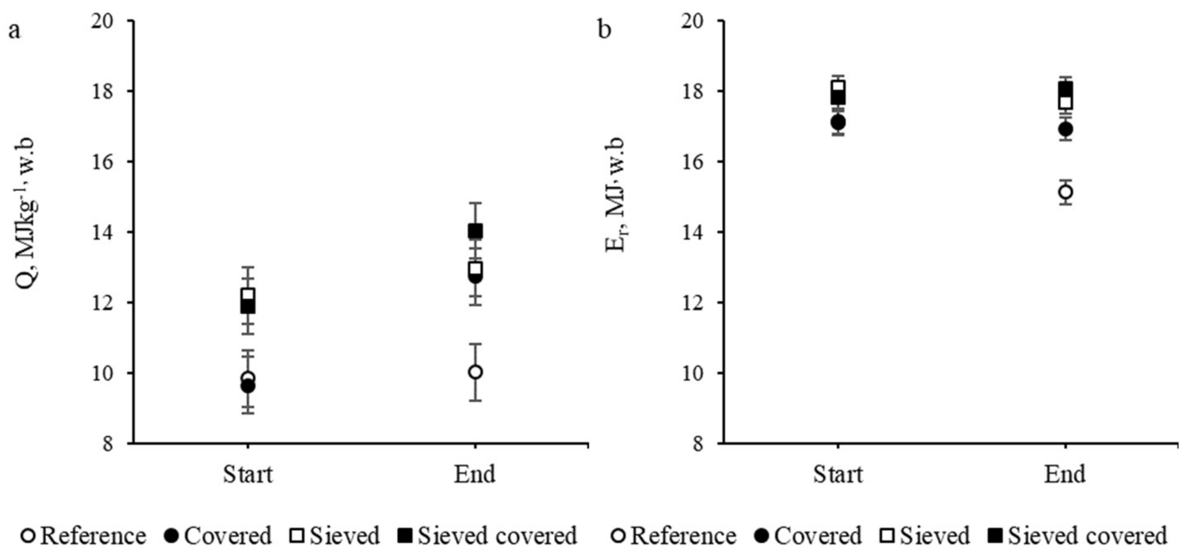

Figure 6. Average values and 95% CI of the net calorific value (Q), expressed on a wet weight basis (**a**) and recovered energy (E_r) per 1 kg dry initial mass expressed on a wet weight basis (**b**) for unsieved and sieved wood chips during storage.

The total effect of alternative storage methods on the average amount of accessible energy for initial mass showed that the initial accessible energy (E_r) of unsieved chips was 17.10 MJ kg^{-1}, initial dry weight $\pm$ 0.80 SD and 17.95 MJ kg^{-1} initial dry weight $\pm$ 0.77 in sieved chips (Figure 6). The E_r in chips stored following the reference method decreased significantly ($p < 0.01$) while the average E_r in sieved and covered piles did not.

Assuming an average energy price at the industry gate of 19.08 € MWh^{-1}, which corresponds to the average cost in Sweden in 2020 [31], the chips' initial value corresponded to 90.63 € per dry ton for unsieved chips and 95.14 € for sieved. After storage, the value of chips stored according to the reference method decreased to 80.21 € (by 11.5%) and the value of uncovered sieved chips decreased to 92.95 € (by 2.3%). The use of an additional covering reduced the value of the unsieved chips to 89.53 €, a 1.2% loss, but increased the value to 96.41 €, by 1.34%, when sieved.

4. Discussion

The present study confirms the positive effects of permeable covers found in earlier studies on chip storage [15,17,22]. Sieving the chips prior to storage further reduced dry matter and energy losses in the studied fraction.

This study investigated the storage of chips in full-scale commercial operations. Storage piles were created using existing industrial practices. The piles had similar shapes, heights and base sizes at all three locations/blocks to enhance comparability, ensuring identical initial conditions. The overall comparison refers to storage treatment and its effect on fuel quality, assessable energy content and value. According to the desired objectives, the design included one observation per treatment combination and block, which was a prerequisite to replicate the commercial storage conditions in full-scale piles. The total volume of stored material amounted to 5.974 m^3, which required a storage area of a minimum of 15.000 m^2, including the fire protection zones. Due to limited storage space at industry fuel yards, a trial with, for example, three replicates at each location would be desirable from a statistical point of view but was too expensive and impractical to carry out within the budget of this project. An option could have been to split the design into two sub-studies. However, the chosen design included three blocks, entailing local variations in precipitation and ambient temperature and providing biomass from different origins, comminution using different types of equipment and, thus, biomass with different compositions and fuel quality. Despite the design, significant and clear differences between treatment combinations could be demonstrated. Overall, this means the general comparison between treatments becomes more valid and robust and easier to generalise.

Comminution was carried out in connection with the trial in block 1 and block 3, while chips had been pre-stored in block 2. This may explain why sieving did not affect the initial M in block 2, since the pre-stored chips were homogenised before the storage trial. Biomass is hygroscopic and easily affected by precipitation. Thus, precipitation affects the result, which explains why the uncovered material, especially at the piles' surface, was rewetted when there was precipitation. In addition, fines have a higher surface-area-to-volume ratio and are more easily rewetted than larger fractions. The initial freshness of biomass affects biological activity as an effect of the amount of easily degradable sugars. However, microbes are already established and the degradation is ongoing in pre-stored biomass; thus, it is initially faster.

The temperature development reflects the combined effect of the activity within piles. Most of these are linked to biological and chemical degradation, which leads to DML. Heat transfer dynamics are affected by the airflow within piles, which is a function of many parameters, notably particle size and particle shape [36]; the permeability in unsieved chip piles is low. This, combined with a high surface-area-to-volume ratio, makes the material easily rewetted, and more readily available sugars create optimal degradation conditions. The temperature development illustrated higher activity within unsieved piles, and the obtained DML confirmed the results. Sieving increases permeability and reduces the number of fines, making the biomass less prone to decomposition. The use of an additional cover prevented rewetting but when combined with sieving, only added extra value for unsieved chips in these trials.

Sieving improves fuel quality, homogenises the fuel, increases its initial value and increases storability. However, it introduces an extra cost and creates a side stream of less-valuable fine fraction (rejection) for which there must be a provision. The price for the sieving operations studied in conjunction with the current storage trial was just under € 2 per MWh or about 10% of the value of the chips [31], but there is potential to reduce this through better work organisation and the use of stationary equipment. More concerning is that in four out of five trials, 21 to 27% of the residue chips were separated as fines, and in block 1, an extremely high 46% were fines. Kons et al., (2015) [37] reported corresponding values of 15% $\pm$ 3 SD–19% $\pm$ 5 SD for comminuted fresh and stored LR chips, respectively. This rejected fraction can be used as a fuel in some boilers. Other alternative uses, such as briquette production, pyrolysis and as an additive to biogas production and other biomass services, are also conceivable. Storage of fines is not recommended due to high M, A and nutrient content. An advantage is that M was reduced in the accepted fraction compared to the unsieved chips in two of the three trials, which in itself increases the economic value of that fraction by 5% per dry ton.

Increased storability of the sieved and covered chips implies reduced storage risks, leading to new options for improvements within the supply chain. Assuming the use of reject fines as fuel, this improved storability may only cover sieving costs. Combining increased storability with reduced risks associated with storage, such as a lower risk of self-ignition, and enabling a higher utilisation of chippers and chip trucks in the supply chain would both improve the supply chain system and reduce costs. However, as both the sieving and covering of the chips comes at a price, it might not be economically feasible to do both. The demand for the value of the fines probably will be the deciding factor between treatments.

5. Conclusions

Sieving improves fuel quality and storability, reducing losses and the risk of self-ignition. Sieving has to be carried out just after comminution to obtain the maximum benefit. Our study did not show that combined sieving and covering yielded any significant reduction of DML, but the effect of treatment was significant for M. However, the combination of sieving and additional covering resulted in an average of 29.7% lower

DML compared to sieving, and increasing the number of replicates would much likely result in a significant difference at p levels < 5%. The effect reduces over time, which indicates that covering is more justified for short storage times. However, these indicative findings call for performing replicates. The value added by sieving may not prove sufficient motivation alone, without combining increased storability, reduced risks and supply chain improvements that come from enabling a higher utilisation rate of chippers and chip trucks.

Author Contributions: E.A. conducted the main part of the planning of the study and wrote the application together with L.E. and D.B., E.A., D.B., L.E. and J.R. contributed to collection of samples at the field trials. E.A. and L.E. performed the statistical analysis and were the initiators of the manuscript. The manuscript was written by E.A. and L.E. with input from D.B. and J.R. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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