

Research paper

The impact of extra long-term storage of logging residues on fuel quality in Estonian conditions – a case study

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Abstract. The reduction of greenhouse gas (GHG) emissions demands a significant increase in the use of wood as a renewable energy source. However, environmental restrictions determine limits on the further growth of harvesting volume. Therefore, a viable solution to enhance the share of energy wood in Estonia's energy balance involves focusing on less exploited assortments of raw material and implementing precise logistics planning. In recent years, mild winters have posed challenges to the extraction of residues and local transport of wood fuels, taking place on soft and unfrozen soils. In such conditions, ensuring a reliable supply of wood fuels becomes rather complicated. When piles of logging residues on unfrozen soils are inaccessible, there is a need to process older piles. The quality of wood chips from such piles is lower compared to the norm. To investigate the impact of extra long-term storage of residues in piles, a study was conducted at the Järvselja Training and Experimental Forest Centre. In 2010, sample piles were created in birch and spruce final felling areas. Over an eight-year period, samples were regularly taken from the piles to analyse the properties of woody biomass during storage. The study results indicate that the quality of fuel from covered piles changes slowly during the first two years of storage. Subsequently, the degradation speed equalizes in both uncovered and covered piles. Despite extensive degradation and loss of dry matter during long-term storage (approximately 29% for Norway spruce and 55% for silver birch after eight years), the quality of dry fuels still meets standard requirements and remains acceptable for boiler houses.

Key words: logging residues, long-term storing, quality, Norway spruce, silver birch.

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Introduction

Estonia has formally ratified the Paris Agreement on Climate Change, aligning with the EU commitment to reduce greenhouse gas (GHG) emissions. In accordance with the 'Estonia 2035' development strat-

egy and the Long-term Development Programme for the Estonian Energy Sector up to the year 2035 (ENMAK 2035, 2023), the national objective by 2050 is to achieve an 80% reduction in GHG emissions compared to 1990 levels, aiming to become a climate-neutral country. To attain these

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ambitious goals, there is a significant emphasis on increasing the utilization of wood as a renewable energy source.

While the annual increment of Estonian forests is estimated at about 16 million cubic meters (Mm³), environmental constraints designate 33.2% of forest areas for protection (Forest, 2023), limiting the further growth of harvesting volume. Consequently, one solution to augment the share of energy wood in Estonia's energy balance involves focusing on less exploited assortments of raw materials and meticulous logistics planning.

In recent years, milder winters have posed challenges to the extraction of residues and local transport of wood fuels on soft and unfrozen soils. This situation complicates the reliable supply of wood fuels. In instances where logging residues on unfrozen soils are inaccessible, there is a necessity to process older piles of logging residues. The quality of wood chips derived from such piles is lower compared to the norm.

Research on the storage of logging residues (Filbakk *et al.*, 2011; Jirjis, 1995; Jirjis & Lehtikangas, 1993; Nilsson *et al.*, 2013;

Nurmi & Hillebrand, 2001; Routa *et al.*, 2015a, 2015b, 2016, 2018) and wood chips (Anerud *et al.*, 2018; Hofmann *et al.*, 2018; Kuptz *et al.*, 2020; Nurmi, 1999; Pari *et al.*, 2017; Whittaker *et al.*, 2018) has consistently shown biomass loss during storage, emphasizing the need to limit storage time. However, existing studies predominantly cover short-term storage, up to 18 months, with little attention given to long-term storage, exceeding two years. Under specific circumstances, there is a demand to utilize older piles of logging residues. Hence, the objective of this study is to investigate the impact of extra long-term storage (up to 8 years) on the properties of logging residues as fuel.

Material and Methods

In 2010, sample piles were established in the Järvelja Training and Experimental Forest Centre, specifically in compartments JS177 (subcompartment 8) and JS207 (subcompartment 3), to monitor the degradation process of logging residues. The piles



Year 2010



Year 2012



Year 2014



Year 2018

Figure 1. Sample pile of spruce logging residues.



Figure 2. Sample pile of birch logging residues.

were created in final felling areas of birch (*Betula* spp.) and spruce (*Picea abies* (L.) H. Karst.), employing two storage methods – uncovered and covered piles (Figures 1 and 2).

Samples were systematically collected from four types of piles, totalling 17 times over an 8-year period from 2010 to 2018 (Table 1). The purpose was to analyse various properties of woody biomass during storage, including ash content, wood density, moisture content, and calorific value. The analyses adhered to established standards for determining the properties of solid biofuels (EVS-EN ISO 18122, 2015; EVS-EN ISO 18125, 2017; EVS-EN ISO 18134-2, 2017).

Additionally, the diameter drying shrinkage was computed for each sample. This involved measuring the diameter of the branch section in two directions before and after drying. The relative diameter shrinkage (Shr) was calculated by dividing the difference between the wet and dry wood diameter by the wet sample diameter. It was essential to establish a consistent moisture content for this calculation, and

the decision was made during the initial sampling on 16 June 2010 (Table 1). The logging residues had been standing and drying in the clear-cutting area, and it was determined to use the base moisture content which was 24.53% for Norway spruces and 25.60% for silver birches.

Table 1. Dates of samples.

No	Date of sampling	Days from the start of the experiment
1	16.06.2010	0
2	02.09.2010	78
3	22.11.2010	159
4	07.03.2011	264
5	02.09.2011	443
6	15.02.2012	609
7	25.04.2012	679
8	04.06.2012	719
9	24.08.2012	800
10	23.11.2012	891
11	16.05.2013	1065

Table 1 continues

No	Date of sampling	Days from the start of the experiment
12	26.11.2013	1259
13	25.06.2014	1470
14	12.12.2014	1640
15	26.08.2015	1897
16	28.08.2016	2265
17	18.03.2018	2832

To characterize the alterations in the properties of logging residues, ANCOVA or regression analysis was employed, utilizing the *lm* function within the statistical software R (R Core Team, 2019). Subsequently, the ANCOVA equation format was employed to estimate various properties of logging residues, including ash content, moisture content, bulk density, calorific value, shrinkage of diameter, or energy density, represented by the equation:

$$Y = a_0 + a_1 \cdot t + a_2 + a_3 + a_4 + a_5 \cdot t \cdot Sp + a_6 \cdot t \cdot C + a_7 \cdot t \cdot P, \quad (1)$$

where Y – ash content, moisture content, bulk density, calorific value, shrinkage of diameter or energy density; %; t – days from the start of the experiment; a_2 – the coefficient for Norway spruce species, and it is zero for silver birch species; a_3 – the coefficient for an uncovered pile, and it is zero for a covered pile; a_4 – the coefficient for a sample taken from the top of the pile, and it is zero for a sample from the middle of the pile; Sp – species parameter (silver birch – 1, Norway spruce – 2); C – covering parameter (covered – 1, uncovered – 2); P – placement parameter (in the middle of the pile – 1; on top of the pile – 2).

In order to determine the loss of wood mass, it is relevant to establish various relationships within the data. Initially, the correlation between the drying shrinkage of wood diameter (Shr) and the moisture content, as well as the duration of storage,

was identified through regression analysis. This involved employing two distinct equations for Norway spruce (Equation 2) and silver birch (Equation 3):

$$Shr_{spruce} = a_1 \cdot \frac{M_{ar}}{t + 1} + a_2 \cdot \ln(t \cdot M_{ar} + 1), \quad (2)$$

$$Shr_{birch} = a_0 + a_1 \cdot M_{ar} + a_1 \cdot t^{M_{ar}} + a_3 \cdot t^2, \quad (3)$$

where $Shr_{species}$ – drying shrinkage of diameter, %; M_{ar} – moisture content, %; t – days from the start of the experiment; a_0, a_1, a_2, a_3 – equation parameters.

In the regression analysis, an equation (Equation 4) was employed to explain the impact of the season on moisture content:

$$M_{ar} = a_0 + a_1 \cdot Month + a_2 \cdot Month^2, \quad (4)$$

where M_{ar} – moisture content, %; $Month$ – the sequence number of the month per year (January – 1, February – 2, etc.).

Subsequently, using the base moisture content values (Norway spruce – 24.53% and silver birch – 25.60%) and the number of days since the start of the experiment, the diameter drying shrinkage from base moisture to oven dry was computed for each sample utilizing Equations 2 or 3. Following this, the relative volume of logging residues was calculated at base moisture, considering oven-dry volume as 1:

$$V = \left(\frac{1}{1 - \frac{Shr}{100\%}} \right)^2, \quad (5)$$

where V represents the relative volume at the base moisture compared to the oven-dry volume; Shr indicates the drying shrinkage of the diameter from the base moisture content, %.

The bulk density of the absolute dry material (ρ_{od}) was assessed for each sample. To calculate the loss of matter during storage, it was necessary to determine the

density, which defines the ratio of absolute dry mass to the volume at base moisture content (ρ_{bm}):

$$\rho_{bm} = \frac{\rho_{od}}{V}, \quad (6)$$

where ρ_{od} – the bulk density of the oven-dry material; ρ_{bm} – the bulk density with oven-dry mass and volume at the base moisture content; V – the relative volume at the base moisture compared to the oven-dry volume.

Regression analysis was subsequently employed to investigate the correlation between storage time and the density of the samples, which was calculated based on dry weight and the initial moisture content volume:

$$\rho_{bm} = a_0 \cdot e^{a_1 \cdot t}, \quad (7)$$

the linear form of this equation is expressed as:

$$\ln(\rho_{bm}) = \ln(a_0) + a_1 \cdot t, \quad (8)$$

where ρ_{bm} – the bulk density with oven-dry mass and volume at the base moisture content; t – the number of days from the commencement of the experiment; a_0, a_1 – parameters of the equation.

The assessment of energy loss during the storage of logging residues involved the application of the aforementioned equations. Initially, the net calorific value of the dry matter was computed across various storage durations, ranging from 0 to 3,000 days (Equation 1). Subsequently, a relative net calorific value was derived for distinct storage durations, with the calorific value at the onset of the experiment (0 days) set as the reference point at 100% (R_q).

In the second step, the bulk density of the material at different time intervals was determined using Equation 7, employing oven-dry mass and volume at the base moisture. Next, a relative density was estab-

lished, considering the material's density at the commencement (0 days) as 100% (R_ρ).

The relative remaining energy content for diverse storage durations was ascertained by multiplying the relative net calorific value by the relative bulk density using the formula:

$$R = R_q \cdot R_\rho, \quad (9)$$

where R – relative remaining energy content, %; R_q – relative net calorific value, %; R_ρ – relative bulk density, %.

Results and Discussion

ANCOVA was employed to explain the temporal evolution of logging residues properties, as delineated by Equation 1. The outcomes of the analysis are detailed in Table 2, encompassing the statistical parameters associated with the calculation equations for diverse properties. Table 3 displays the parameter estimates derived from Equation 1, along with their corresponding significance probabilities.

The subsequent figures illustrate the influence of storage duration on the characteristics of residues. As depicted in Figure 3, the ash content of all sample types did not surpass 2% within the initial three years of storage. Prolonged storage revealed a noticeable rise in the ash content of birch logging residues, with the highest levels observed in covered birch residues. In contrast, the ash content of spruce residues remained constant throughout the observation period. The lowest ash content was observed in uncovered spruce residues. The extended storage of wood chips derived from Mediterranean poplar plantations revealed a gradual increase in ash content, rising from 2.91% to 3.31% over an 18-month period (Pari *et al.*, 2017). The observed elevation in ash content surpasses that observed in the analysis of logging residues in this study.

Table 2. Results of ANCOVA of different characteristics (Equation 1).

Dependent variable (Y)	p-value	Standard error	R ²	Figure
Ash content	0.0032	0.4825	0.1286	3
Net calorific value of dry matter	<0.0001	0.1026	0.2120	4
Net calorific value of moist fuel	<0.0001	0.6905	0.3940	5
Bulk density	<0.0001	0.0733	0.7789	6
Energy density	<0.0001	0.3962	0.7718	7
Shrinkage of diameter	0.0015	1.3550	0.0989	8

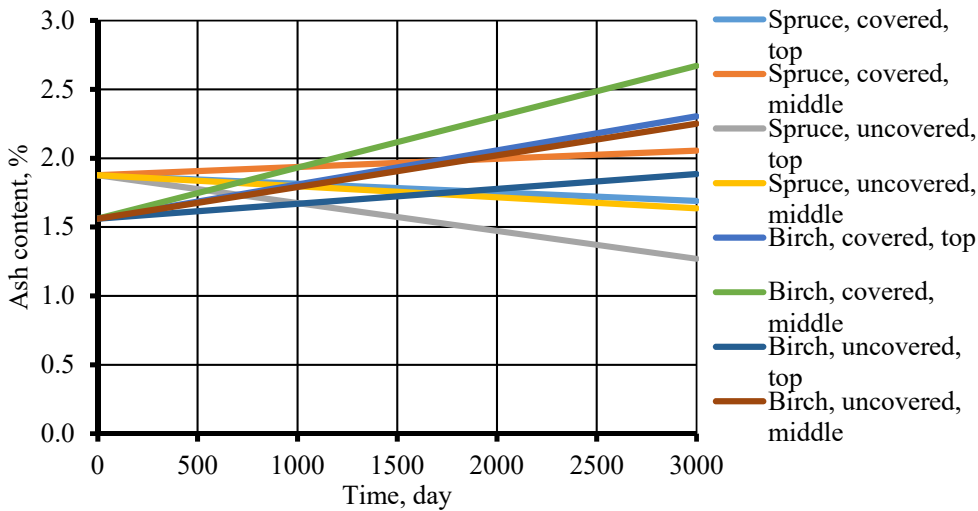


Figure 3. Change of ash content during storage.

The net calorific value of dry matter in logging residues exhibits a consistent upward trend during storage, as illustrated in Figure 4. Conversely, the net calorific value of moist fuel demonstrates a decline, as depicted in Figure 5, with birch experiencing a more rapid decrease. Covered storage piles maintain a higher net calorific value for moist fuel in comparison to uncovered piles. Additionally, both bulk density and energy density decrease during storage, as evidenced by Figures 6 and 7.

Furthermore, prior research has addressed the issue of dry matter loss. In Norway, the dry matter loss in softwood logging waste was reported to be between

1 and 3% per month (Filbakk *et al.*, 2011), a rate exceeding that observed in our current study. Routa *et al.* (2015a, 2016) documented a dry matter loss ranging from 0–2.9% per month over an 8-month period, and in a more extended study spanning 10.2–14.5 months, the observed dry matter loss was in the range of 0.07% to 0.95% per month (Routa *et al.*, 2018). These findings are consistent with our own results. A study conducted in Sweden on the storage of common spruce wood chips (including small amounts of pine and birch wood chips) for a period of 7 months revealed a dry matter loss of 5.8% for the covered pile compared to 7.3% for the uncovered pile (Anerud *et*

Table 3. Estimations and significance probabilities of parameters of ANCOVA Equation 1.

Dependent variable (Y)	Figure	Parameter	Estimation	p-value
Ash content, %	3	a_0	1.561477	<0.0001
		a_1	0.000941	<0.0001
		a_2	0.315644	0.0230
		a_5	-0.000310	0.0045
		a_6	-0.000140	0.0341
		a_7	-0.000122	0.0633
Net calorific value of dry matter, kWh/kg	4	a_0	5.323000	<0.0001
		a_1	0.000085	0.0081
		a_5	-0.000039	0.0052
		a_7	0.000021	0.1380
Net calorific value of moist fuel, kWh/kg	5	a_0	4.162196	<0.0001
		a_1	-0.001087	<0.0001
		a_3	-0.643537	<0.0001
		a_5	0.000423	<0.0001
Bulk density, g/cm ³	6	a_0	0.571200	<0.0001
		a_1	-0.000160	<0.0001
		a_2	0.173900	<0.0001
		a_3	-0.042530	0.0013
		a_5	0.000046	0.0069
Energy density, MWh/m ³	7	a_0	3.055000	<0.0001
		a_1	-0.000846	<0.0001
		a_2	0.925200	<0.0001
		a_3	-0.232900	0.0012
		a_5	0.000248	0.0068
Shrinkage of diameter, %	8	a_0	4.284253	<0.0001
		a_2	-0.791850	0.0012
		a_6	0.000150	0.0973

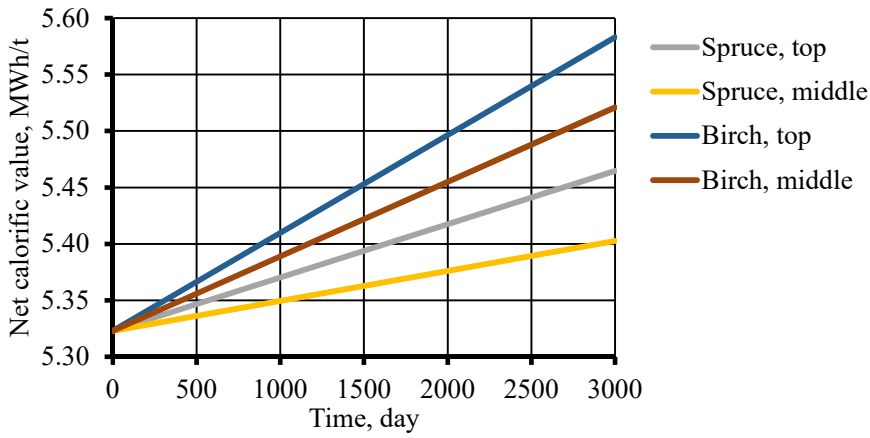


Figure 4. Change of net calorific value of dry matter.

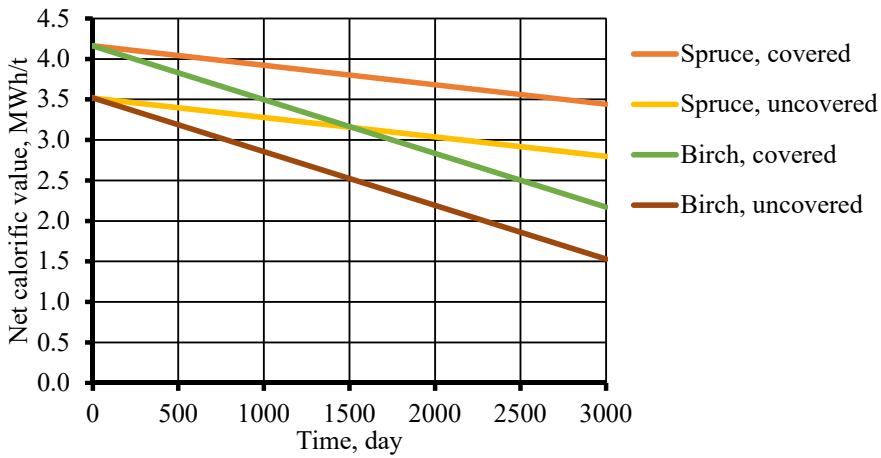


Figure 5. Change of net calorific value of moist fuel.

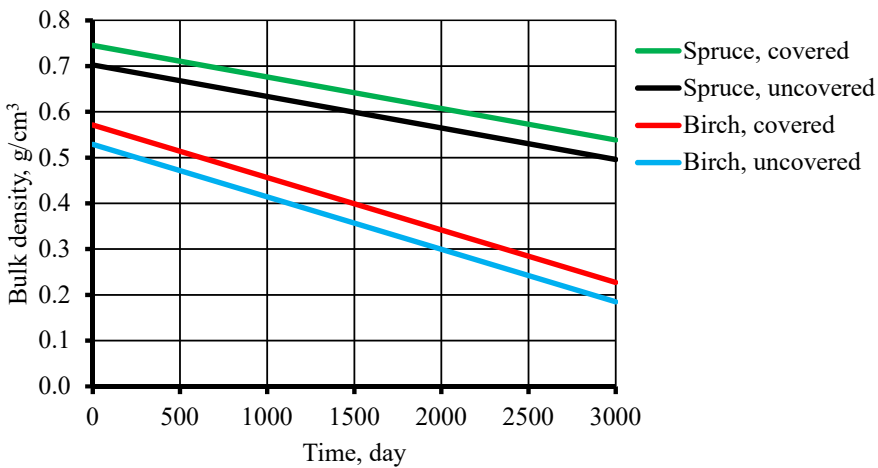


Figure 6. Change of bulk density.

al., 2018). In a study conducted in Bavaria, where wood chips (produced from spruce logging residues) were stored from May to October (153 days), a dry matter loss of 7.4% was observed (Kuptz *et al.*, 2020). Another study carried out in Bavaria, focusing on the storage of wood chips derived from typical spruce logging residues in stacks, unveiled a monthly dry matter loss ranging from 0.7% to 2.2% (Hofmann *et al.*, 2018). In a study conducted in the United Kingdom, the storage of willow wood chips in stacks for six months resulted in a dry matter loss ranging from 19.8% to 22.6% (Whittaker *et al.*, 2018). According

to the findings of these studies, it can be inferred that the loss of dry matter when storing as wood chips is greater than when storing as logging residues.

Figure 8 demonstrates that storage leads to an increase in the drying shrinkage of wood samples over time.

As observed by Nilsson *et al.* (2013) in Sweden, the moisture content in wood piles during the summer months typically ranges from 30–40%. Figure 9 depicts the considerable variation in moisture content throughout the year, exceeding 20%. This variability suggests that selecting an opportune moment for chipping residues can

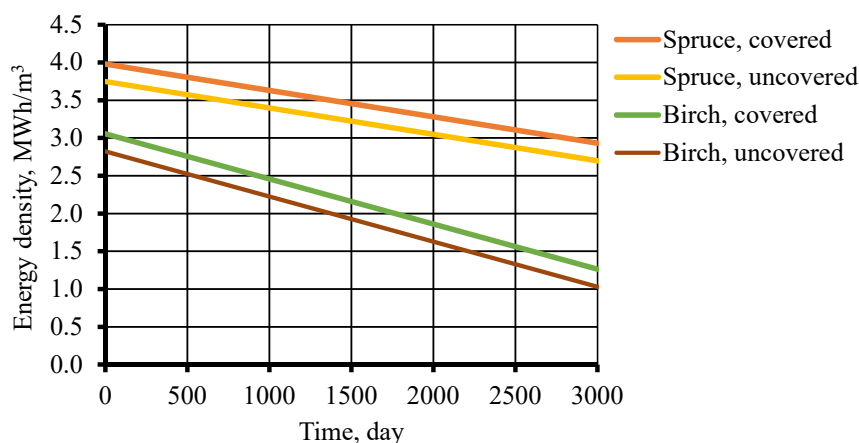


Figure 7. Change of energy density.

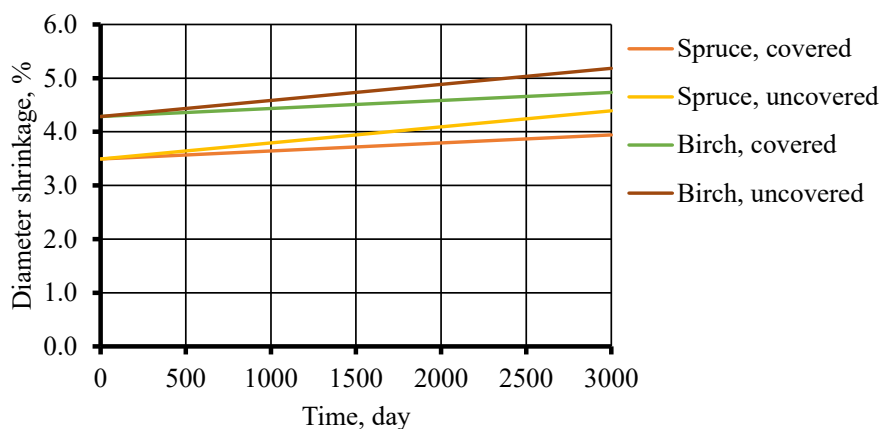


Figure 8. Shrinkage of diameter of sample branches.

Table 4. Relationship between moisture content and month number (Equation 4).

Sample	a_0	a_1	a_2	p-value	Standard error	R ²
Birch, covered	58.654	-7.687	0.423	0.0235	8.289	0.415
Birch, uncovered	78.481	-11.882	0.863	0.0967	12.862	0.284
Spruce, covered	57.448	-9.080	0.561	0.0428	8.637	0.363
Spruce, uncovered	65.693	-10.981	0.722	0.0407	9.484	0.367

significantly enhance the quality of wood chips. Additionally, Figure 9 presents the equations derived from the regression analysis (Equation 4), with parameter estimates detailed in Table 4. During the summer, characterized by lower precipitation and warmer weather, the moisture content of logging residues decreases. Conversely, during the autumn-winter period, the moisture content increases, which is consistent with findings in other studies (Jirjis & Lehtikangas, 1993; Nurmi, 1999; Nurmi & Hillbrand, 2001). A study in Finland indicates that uncovered piles have an approximately 5% higher moisture content than covered piles in winter (Routa *et al.*, 2015b). Our results, as shown in Figure 9, confirm this for

Norway spruce logging residues. However, for birch logging residues, the uncovered pile exhibits over 10% more moisture content than the covered pile.

In Figures 10 and 11, the influence of storage duration and humidity on the shrinkage of diameter and alteration in the moisture content of birch and spruce branches is illustrated. To characterize the correlation between drying shrinkage, storage time, and moisture content, regression analysis was employed. Equation 2 was utilized for the Norway spruce dataset, while Equation 3 was applied to the silver birch data. The parameter estimates resulting from the regression analysis are presented in Table 5.

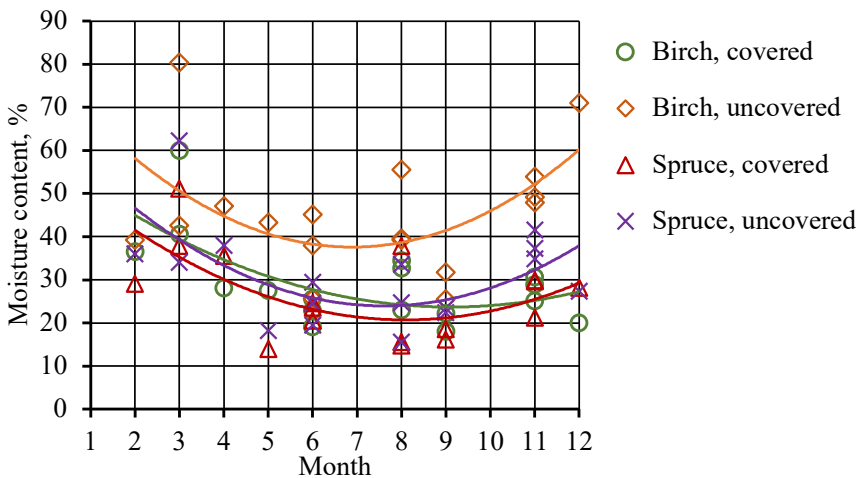


Figure 9. Variation of moisture content during the year.

Table 5. Parameter estimates for the relationship between drying shrinkage, storage time, and moisture content (Equation 2 and 3).

Species	Parameter	Estimation	p-value
Silver birch	a_0	3.851	<0.0001
	a_1	0.02156	0.0432
	a_2	$3.572 \cdot 10^{-283}$	<0.0001
	a_3	$-1.944 \cdot 10^{-7}$	0.0175
	R^2	0.240	
	SE	1.098	
	p	0.0010	
Norway spruce	a_1	0.15284	<0.0001
	a_2	0.37387	<0.0001
	R^2	0.937	
	SE	0.990	
	p	<0.0001	

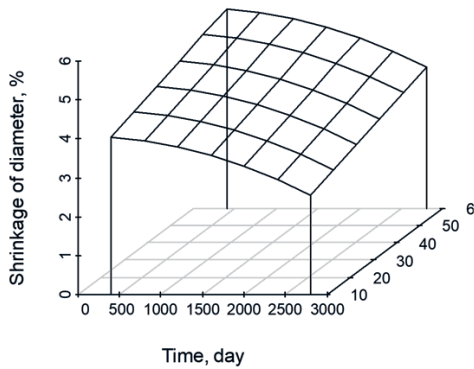


Figure 10. Diameter drying shrinkage relationship with storage time and moisture content in birch logging residues.

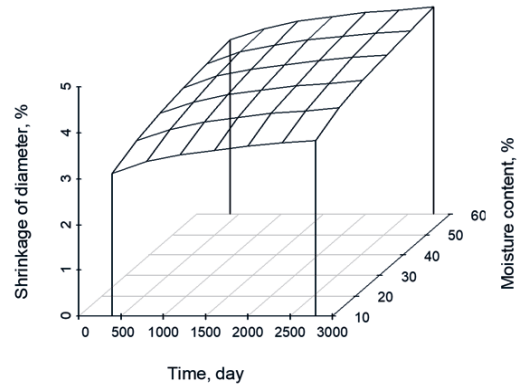


Figure 11. Diameter drying shrinkage relationship with storage time and moisture content in Norway spruce logging residues.

The drying shrinkage percentage of the diameters of silver birch logging residues decreases during storage, with the rate of decrease initially slow and progressively accelerating over time (Figure 10). Conversely, for spruce, an opposite trend is observed, where the drying shrinkage of diameters increases with time (Figure 11). Initially, the shrinkage undergoes a faster change, followed by a slower rate of change.

The disparity in shrinkage between birch and spruce can be attributed to the distinct characteristics of these tree species.

Shrinkage is known to be influenced by specimen dimensions, drying speed, and density (Bowyer *et al.*, 2003). In the case of birch, the reduction in drying shrinkage can be explained by the decrease in density. Denser wood typically exhibits higher drying shrinkage, whereas wood with lower density tends to have lower shrinkage (Saarman & Veibri, 2006). However, explaining the increase in drying shrinkage of spruce logging residues is challenging, as the density of spruce logging residues also decreased during storage.

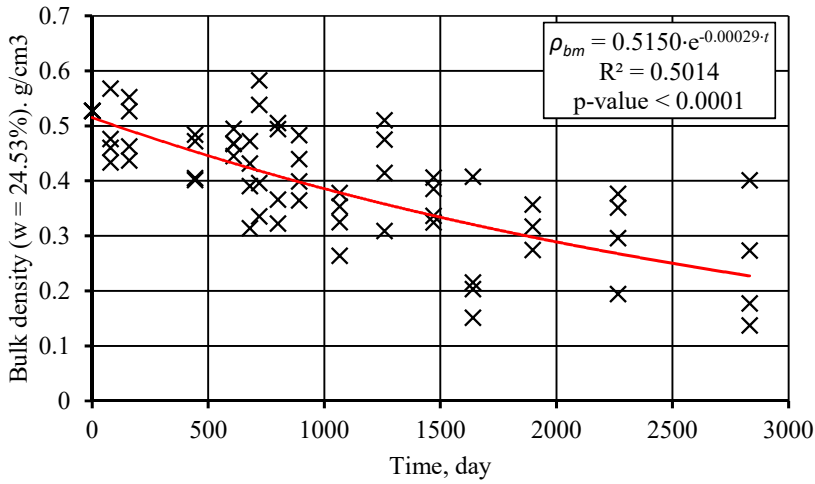


Figure 12. Bulk density during storage of birch residues (ρ_{bm} – bulk density with oven-dry mass and volume at the base moisture content; t – days from the start of the experiment).

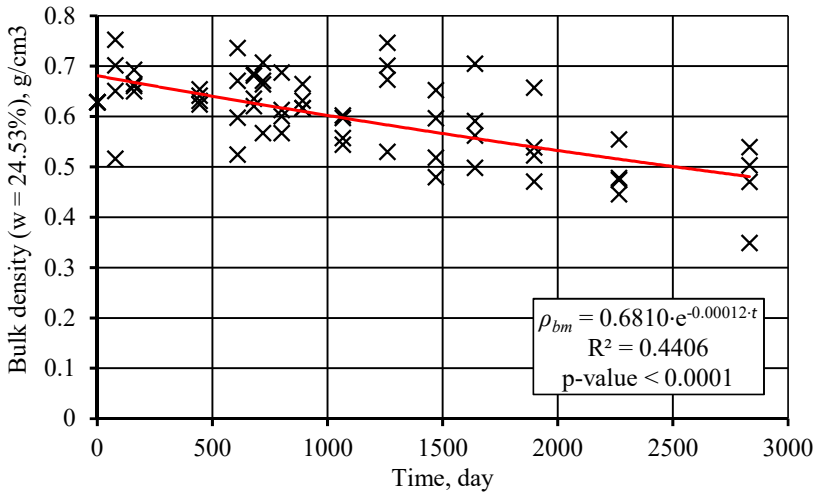


Figure 13. Bulk density during storage of spruce residues (ρ_{bm} – bulk density with oven-dry mass and volume at the base moisture content; t – days from the start of the experiment).

Analysing the changes in the bulk density of residues during storage (see Figures 12 and 13), the decline in the energy content of logging residues over long-term storage was calculated, and the results are illustrated in Figure 14.

The energy loss incurred during the storage of logging residues was determined by applying the net calorific value of the dry matter (Equation 1, Figure 4).

Additionally, the bulk density, calculated using the oven-dry mass and volume at the base moisture, was assessed at various time points (Equation 7, Figures 12 and 13). Utilizing Equation 9, the residual energy content for different storage periods was computed and presented in Figure 14 and Table 6.

In their study, Anerudi *et al.* (2018) observed that the energy loss of wood chips

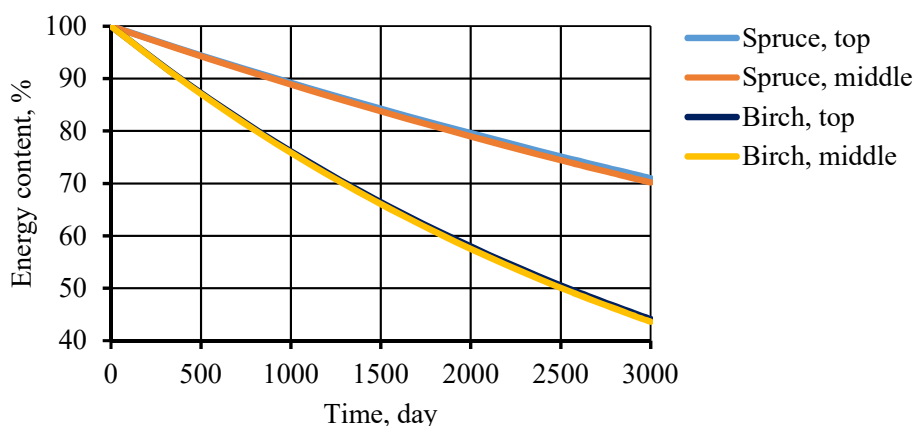


Figure 14. Decline of energy content of logging residues during long-term storage.

(primarily from Norway spruce and to a lesser extent from Scots pine and birch) of 0.6% when stored in a covered pile and 5.3% when stored in an uncovered pile over a 7-month period.

Table 6. Decline of energy content of logging residues during long-term storage by species and place in pile.

Storage time, year	Spruce, top	Spruce, middle	Birch, top	Birch, middle
0	100.0	100.0	100.0	100.0
1	95.9	95.8	90.5	90.4
2	92.0	91.7	81.9	81.7
3	88.2	87.9	74.2	73.9
4	84.6	84.2	67.1	66.8
5	81.2	80.6	60.8	60.4
6	77.9	77.2	55.0	54.5
7	74.7	73.9	49.8	49.3
8	71.6	70.8	45.1	44.6

The data illustrates the decline in energy content of the logging residues during long-term storage, differentiated by species and pile placement over an 8-year period. Notably, birch exhibits a higher loss of dry matter compared to spruce. The 8-year observation indicates approximately a 30% drop for spruce and over 50% for

birch. This degradation, attributed to micro-organisms and various processes, also results in a decline in the energy density of the fuel.

Despite the extensive degradation during extra long-term storage, it is noteworthy that the quality of dry fuels remains compliant with standards and remains acceptable for use in boiler houses.

Conclusions

The combustion properties of logging residues as fuel are significantly influenced by their moisture content and bulk density. These two factors have a cascading effect on other properties. Notably, the moisture content of covered piles was found to be lower than in uncovered piles. The ash content, however, exhibited different trends for silver birch and Norway spruce logging residues during the storage period. Silver birch residues showed an increase, while Norway spruce residues demonstrated a decrease. Overall, the ash content did not exhibit a strong dependence on storage time.

Examining the relationship between the net calorific value of dry matter and storage time revealed that silver birch logging residues experienced a greater increase

in calorific value compared to Norway spruce. The increase in the net calorific value was attributed to the breakdown of hemicellulose and cellulose, leading to a higher proportion of lignin with a higher calorific value.

The bulk density and energy density of silver birch logging residues decreased at a faster rate than those of Norway spruce. The uncovered logging residues of both tree species had a lower energy density compared to the covered ones. Additionally, the moisture content was lower in summer months than in winter.

Diameter drying shrinkage had a significant correlation with storage time, with silver birch residues experiencing greater reduction than Norway spruce. Organic matter loss during storage was more pronounced in silver birch compared to Norway spruce. The decrease in the density of dry mass per volume unit was significantly higher in silver birch over the storage period, leading to a faster decline in energy density.

In practical terms, it is recommended that the storage time for logging residues should not exceed one or two years due to extensive degradation and dry matter loss. Despite this, the quality of dry fuels remains acceptable and meets standard requirements even after longer storage, making them suitable for use in boiler houses.

References

- Anerud, E., Jirjis, R., Larsson, G., Eliasson, L. 2018. Fuel quality of stored wood chips – Influence of semi-permeable covering material. – *Applied Energy*, 231, 628–634. <https://doi.org/10.1016/j.apenergy.2018.09.157>.
- Bowyer, J.L., Shmulsky, R., Haygreen, J.G. 2003. *Forest Products and Wood Science: An Introduction*. 4th Edition. Ames, Iowa, Iowa State University Press. 554 pp.
- ENMAK 2035. 2023. Strategic assessment of the environmental impact of the Energy Economy Development Plan until 2035. (Energiamajanduse arengukava aastani 2035 keskkonnamõju strateegiline hindamine). [WWW document]. – URL https://kliimaministeerium.ee/enmak_ksh. [Accessed 11 November 2023]. (In Estonian).
- EVS-EN ISO 18122. 2015. Solid biofuels – Determination of ash content. Estonian Centre for Standardisation. [WWW document]. – URL <https://www.evs.ee/en/evs-en-iso-18122-2015>. [Accessed 10 December 2023].
- EVS-EN ISO 18125. 2017. Solid biofuels – Determination of calorific value. Estonian Centre for Standardisation. [WWW document]. – URL <https://www.evs.ee/et/evs-en-iso-18125-2017>. [Accessed 10 December 2023].
- EVS-EN ISO 18134-2. 2017. Solid biofuels – Determination of moisture content – Oven dry method – Part 2: Total moisture – Simplified method. Estonian Centre for Standardisation. [WWW document]. – URL <https://www.evs.ee/en/evs-en-iso-18134-2-2017>. [Accessed 10 December 2023].
- Filbakk, T., Høibø, O.A., Dibdiakova, J., Nurmi, J. 2011. Modelling moisture content and dry matter loss during storage of logging residues for energy. – *Scandinavian Journal of Forest Research*, 26(3), 267–277. <https://doi.org/10.1080/02827581.2011.553199>.
- Forest. 2023. Yearbook Forest 2021. (Aastaraamat Mets 2021). – Sirkas, F., Valgepea, M. (eds.). Tallinn, Keskkonnaagentuur. 337. pp. (In Estonian).
- Hofmann, N., Mendel, T., Schulmeyer, F., Kuptz, D., Borchert, H., Hartmann, H. 2018. Drying effects and dry matter losses during seasonal storage of spruce wood chips under practical conditions. – *Biomass and Bioenergy*, 196–205. <https://doi.org/10.1016/j.biombioe.2017.03.022>.
- Jirjis, R. 1995. Storage and drying of wood fuel. – *Biomass and Bioenergy*, 9, 181–190. [https://doi.org/10.1016/0961-9534\(95\)00090-9](https://doi.org/10.1016/0961-9534(95)00090-9).
- Jirjis, R., Lehtikangas, P. 1993. Fuel quality and dry matter loss during storage of logging residues in a windrow. (Bränslekvalitet och substansförluster vid vältlagring av hyggesrester). – Report No. 236. Uppsala, The Swedish University of Agricultural Sciences. 26 pp. (In Swedish).
- Kuptz, D., Lesche, S., Mendel, T., Mack, R., Rist, E., Schön, C., Hartmann, H. 2020. Fuel properties, dry matter losses and combustion behavior of wood chips stored at aerobic and anaerobic conditions. – *Biomass and Bioenergy*, 142, 105745. <https://doi.org/10.1016/j.biombioe.2020.105745>.
- Nilsson, B., Blom, T., Thörnqvist, T. 2013. The influence of two different handling methods on the moisture content and composition of logging residues. – *Biomass and Bioenergy*, 52, 34–42. <https://doi.org/10.1016/j.biombioe.2013.02.026>.
- Nurmi, J. 1999. The storage of logging residue for fuel. – *Biomass and Bioenergy*, 17, 41–47. [https://doi.org/10.1016/S0961-9534\(99\)00023-9](https://doi.org/10.1016/S0961-9534(99)00023-9).

- Nurmi, J., Hillebrand, K. 2001. Storage alternatives affect fuelwood properties of Norway spruce logging residues. – *New Zealand Journal of Forestry Science*, 31, 289–297.
- Pari, L., Scarfone, A., Santangelo, E., Gallucci, F., Spinelli, R., Jirjis, R., Del Giudice, A., Barontini, M. 2017. Long term storage of poplar chips in Mediterranean environment. – *Biomass and Bioenergy*, 107, 1–7. <https://doi.org/10.1016/j.biombioe.2017.09.007>.
- R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. [WWW document]. – URL <http://www.r-project.org/>. [Accessed 12 December 2023].
- Routa, J., Kolström, M., Ruotsalainen, J., Sikanen, L. 2015a. Precision measurement of forest harvesting residue moisture change and dry matter losses by constant weight monitoring. – *International Journal of Forest Engineering*, 26, 71–83. <https://doi.org/10.1080/14942119.2015.1012900>.
- Routa, J., Kolström, M., Ruotsalainen, J., Sikanen, L. 2015b. Validation of prediction models for estimating the moisture content of small diameter stem wood. – *Croatian Journal of Forest Engineering*, 36, 283–291.
- Routa, J., Kolström, M., Ruotsalainen, J., Sikanen, L. 2016. Validation of prediction models for estimating the moisture content of logging residues during storage. – *Biomass and Bioenergy*, 94, 85–93. <https://doi.org/10.1016/j.biombioe.2016.08.019>.
- Routa, J., Kolström, M., Sikanen, L. 2018. Dry matter losses and their economic significance in forest energy procurement. – *International Journal of Forest Engineering*, 29, 53–62. <https://doi.org/10.1080/14942119.2018.1421332>.
- Saarman, E., Veibri, U. 2006. *Wood Science*. (Puiduteadus). Tartu, Eesti Metsaselts. 560 pp. (In Estonian).
- Whittaker, C., Yates, N.E., Powers, S.J., Misselbrook, T., Shield, I. 2018. Dry matter losses and quality changes during short rotation coppice willow storage in chip or rod form. – *Biomass and Bioenergy*, 112, 29–36. <https://doi.org/10.1016/j.biombioe.2018.02.005>.