FUEL QUALITY, DRY MATTER LOSSES AND COMBUSTION BEHAVIOUR OF ANAEROBICALLY STORED WOOD CHIPS

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ABSTRACT: Anaerobic storage of wood chips from forest residues and from short rotation coppice was investigated regarding dry matter losses and fuel quality changes using three approaches, i.e. small storage container (including greenhouse gas (GHG) measurements), small-scale silos of 2 m^3 volume and a small wood chip pile (12 m^3). After storage, selected wood chip samples were combusted in a 30 kW wood chip boiler and relevant emissions (CO, NO_X, particles) were measured. Container trials allowed for best anaerobic conditions reducing dry matter losses to a minimum of 2 w-% after 5 months of storage. Silos proved not to be completely air tight as moisture content increased by 4.2 to 10.4 w-% due to precipitation and distinct dry matter losses were recorded. Still, dry matter losses were lower in silo trials compared to storage in a pile. During combustion, CO and particle emissions increased in naturally stored materials compared to technically dried fuels, probably due to changes in their woody structure but also due to an increase in chemical elements such as potassium. In conclusion, anaerobic storage seems to be an interesting option to reduce dry matter losses. Future studies should focus on the applicability of this technique under practical conditions (e.g. in large driving silos) and on further combustion trials.
Keywords: wood chip, storage, quality, dry matter, combustion

1 INTRODUCTION

Outdoor storage of fresh wood chips in large storage piles is a typical process step within the wood chip supply chain due to the often occurring temporal differences in fuel supply and demand [1][2]. This is especially relevant when large amounts of wood chips are produced outside of the heating season e. g. during forest protection practices to decrease damages caused by bark beetle attacks or during the harvest of short rotation coppices (SRC) typically done at the end of winter. However, during the storage of wood chips, large dry matter losses may occur due to decomposition of the fresh material by bacteria and fungi [1][3]. These losses might be minimized by using anaerobic storage techniques i.e. by providing unsuitable growing conditions for microbes such as an oxygen depleted atmosphere [4][5].

Anaerobic storage of wood chips might be facilitated by the use of driving silos that are commonly used in agriculture. The application of this technique was tested on a small-scale basis at TFZ.

2 MATERIAL & METHODS

The effect of anaerobic storage of wood chips on fuel quality and dry matter losses was investigated by three different approaches:

- Small storage container (n = 12) were used to assess the effect of anaerobic storage in a laboratory trial focusing not only on dry matter losses but also on GHG emissions due to microbial activity.
- Small-scale concrete silos (n = 6) were build-up to test the practical applicability of driving silos for anaerobic storage.
- A small wood chips storage pile with a fleece cover (n = 1) was used as a reference.

Storage was done for 5 months (May 2018 until October 2018) with fresh wood chips from forest residues (coniferous wood) and from SRC (poplar). All samples derived from the same shipments. Fuel quality and dry matter were assessed before and after storage. In addition, some of the stored materials were used for combustion trials in a small-scale wood chip boiler.

2.1 Storage container trial including GHG sampling

Aerobic and anaerobic storage was investigated in small storage container [6] using both wood chip assortments (n = 3 per assortment and storage method). Wood chips were filled into 0.6 m^3 containers (Figure 1). To ensure a microclimate that is similar to large storage piles, all side walls of the container were insulated. Temperature sensors (Datalogger testo 175-H1, Testo AG) were placed in the middle of each container directly into the bulk material. Temperature was recorded every 10 minutes.

For aerobic storage, container bottoms were perforated with holes (2 cm diameter) to ensure natural aeration. To prevent small particles from falling through the holes, a net was placed on top. For anaerobic storage, containers were not perforated at the bottom. Instead, containers were sealed with a Plexiglas® plate and silicon (Figure 1).

Figure 1: Wood chip storage container (anaerobic variant) with insulation and Plexiglas® sealing

For all containers, the mass of the fuel was determined before and after storage with a platform scale (MT KD600, Mettler-Toledo GmbH). The storage period was 5 months from May until October 2018. Storage was done in a rain and wind protected shelter. Ambient air temperature and air humidity at the storage location were recorded every 10 minutes (Datalogger testo 175-H1, Testo AG). Before and after storage, representative wood chip samples were taken for fuel quality analysis (see section 2.4).

The emissions of relevant greenhouse gases (GHG) that emerge during storage due to microbial activity, i.e. CO, CH_4, CO_2 and C_XH_Y, were determined by sampling the volume and the concentration of these gases in gas sample bags (100 l, Tedlar® Gas sample bag, Restek GmbH) throughout the 5 months storage period. Gases were analysed with gas analysers (CO/CO_2: Uras 26, ABB Group; O_2: Magnos 206, ABB Group and CH_4: FID 1230, Testa GmbH).

2.2 Storage in small concrete silos

To test the applicability of storage in driving silos, six small-scale concrete silos with approx. 2 m^3 filling volume were used (Figure 2).

Figure 2: Small-scale silos for the storage of wood chips (top: silo during build-up; bottom: covering of a silo with wrapping foil and silage foil)

Tests were done with forest residue wood chips (*n* = 3) and SRC wood chips (*n* = 3). Total mass of the whole wood chip batch per silo was determined before and after storage using a platform scale (MT KB60.2, Mettler-Toledo GmbH). Fuel samples were collected before and after storage (see section 2.4).

Silos were covered with both a wrapping and a silage foil. Storage duration was five months from May to October 2018. Each silo was equipped with two temperature sensors (Datalogger testo 175-H1, Testo AG) to monitor the temperature of the bulk material during storage. Silos were stored outside at TFZ without wind or rain protection.

2.3 Storage pile

A small wood chip storage pile of approx. 12 m^3 was used as a reference to the silo and container trials. Only forest residue wood chips were used for pile storage. Pile form was approx. 4 m length, 2 m width and 1.5 m height (Figure 3).

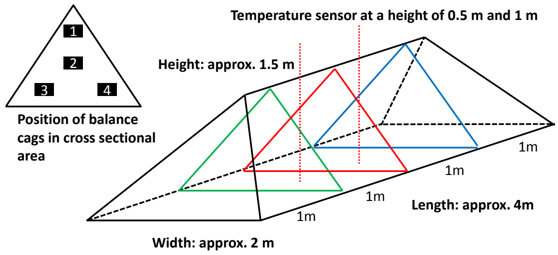

Figure 3: Schematic drawing of the storage pile

Balance bags of approx. 2 l filling volume were used for the determination of dry matter losses and fuel quality changes (Figure 4) [1][3]. In total, 12 balance bags were positioned into the pile in three cross sectional areas at a length of approx. 1 m, 2 m and 3 m (Figure 3). Samples for fuel quality and dry matter losses after storage derived directly from the balance bags (see section 2.4).

Figure 4: Balance bags at position 3 and 4 during build-up of the storage pile.

The pile was equipped with four temperature sensors (Datalogger testo 175-H1, Testo AG), i. e. two sensors at pile length 1.5 m and 2.5 m at a height of 0.5 m as well as 1.0 m. Pile temperature was recorded every 10 min. The storage pile was covered with a semi-permeable fleece cover (PolyTex, 200 g m^{-2}, Zill GmbH & Co. KG). Storage time was 5 months from May to October 2018.

2.4 Fuel quality and dry matter losses

Fuel quality of wood chips, i.e. moisture content, ash content, particle size distribution and net calorific value was analysed before and after storage according to international standards for solid biofuels (Table I). Dry matter losses were determined by measuring the total dry mass of all batches before and after each trial (container trial, silos) or by measuring the dry mass of balance bags (wood chip pile) [1][6]. For container and silo trials, the whole wood chip batch was homogenized manually before sampling. For the storage pile, homogenization was done before filling of the balance bags.

Table I: International standards to determine the fuel quality of solid biofuels

Parameter	Unit	ISO Standard
Moisture content	w-%	18134-2
Ash content (d.b.)	w-%	18122
Net calorific value (d.b.)	MJ kg^{-1}	18125
Particle size distribution	w-%, mm	17827-1

2.5 Combustion trials

Combustion trials were performed with forest residue wood chips from silo storage (see section 2.2) and from pile storage (see section 2.3) but also with technically dried wood chips that were derived from the same shipments in May 2018. All combustion trials were performed with a moisture content of approx. 15 w-%. Before combustion, each wood chip sample had to be chipped one additional time with a stationary drum chipper at TFZ (VTH 45/12/2, Vecoplan, Bad Marienberg) as particle size was too large for the small-scale wood chip boiler.

For technical drying, a self-constructed batch drying system with heated air was used. Two wood chip samples were dried to a moisture content of 15 w-%. One sample was combusted directly after drying while the other sample was also stored for 5 months (i.e. from May to October 2018) in a big bag. In case of samples from silos and from the storage pile, technical drying was also necessary before combustion to ensure a moisture content of 15 w-%.

Wood chip samples were combusted using a 30 kW wood chip boiler (Powerchip 20/30, Guntamatic Heiztechnik GmbH, Figure 5).

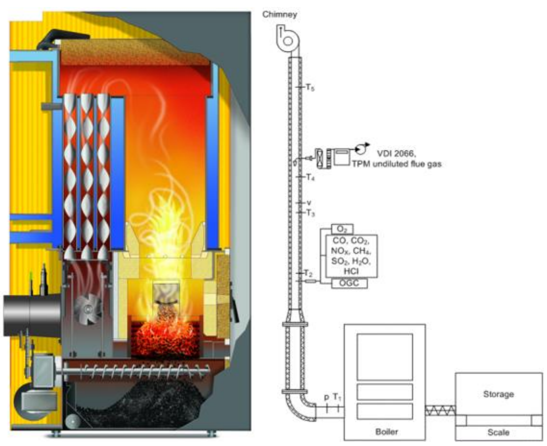

Figure 5: Schematic drawing of the boiler (left) and of the test stand of TFZ (right)

A round storage tank with a flat spring agitator and a screw conveyor was used. To determine the fuel consumption during combustion, the storage tank was placed on a platform scale (Mettler-Toledo GmbH, MT KD600). The heat consumption was permanently regulated to a nominal load of 30 kW (± 8 %) following DIN EN 303-5.

The gaseous components CO, CO_2, and O_2 were determined using a single component analyser (ABB Automation GmbH ABB AO2020), NO_X by a chemiluminescence detector (Eco Physics GmbH CLD 822 Mhr Analysator) and for water vapour content, SO_X, HCl and CH_4 an FTIR-analyser (Ansyco GmbH FTIR DX4000N) was used [7]. The recording interval for the continuous measurement was set to 10 seconds. The total particulate matter (TPM) was measured following VDI 2066-1 (n = 5) applying a filtration temperature during sampling and the filter pre- and post-treatment temperature of 160 °C. The boiler was operated at a constant flue gas draught of -15±2 Pa as it is recommended by the boiler manufacturer. The diameter of the flue gas duct and the connection pipe was 150 mm. The flue gas velocity was continuously measured using a vane anemometer (Höntzsch GmbH, ZS25/25-ZG4) positioned in a narrowed stretch of the measurement section with a diameter of 100 mm.

3 RESULTS UND DISCUSSION

3.1 Wood chip quality before storage

Fuel quality before storage was in a typical range for freshly harvested forest residue wood chips and SRC (Table II) [8]. Mean moisture content was 40.7 w-% and 53.9 w-% for forest residues and for SRC, respectively, indicating that some drying occurred for the forest residue wood chips before the trials. Mean ash content (on dry basis) ranged from 1.5 w-% (forest residues) to 3.3 w-% (SRC) indicating a high amount of woody biomass in forest residue wood chips and some contamination of SRC wood chips, e.g. with mineral soil during harvesting [8].

Table II: Mean fuel quality of forest residue wood chips (FR) and SRC wood chips before storage (d.b. = dry basis)

Parameter	FR	SRC
Moisture content (n = 10)	40.7	53.9
Ash content (d.b., n = 5)	1.5	3.3
Net calorific value (d.b., n = 5)	19.3	18.1

Particle size (n = 5) of forest residue samples was rather coarse with a particle size class P63 according to ISO 17225-1. SRC wood chips could be classified as P45S according to ISO 17225-4.

3.2 Container trials

Temperature inside storage containers was close to ambient temperature throughout the whole experiment (data not shown). This might be due to the overall small size of the storage container [6]. However, during the first month of storage, temperature in aerobically stored container was increased compared to ambient air temperature by approx. 5 K indicating some microbial activity in these variants [1][2][3].

During the storage in containers for 5 months, the total mass of the samples that were stored under aerobic conditions strongly declined, indicating a distinct drying of the material, while the weight of the anaerobically stored wood chips did not differ before and after storage (Figure 6).

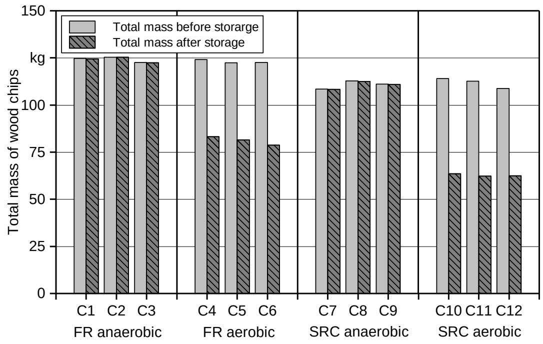

Figure 6: Total mass of wood chips before and after storage in container trials

Moisture content of aerobically stored wood chips decreased during container trials due to drying effects to mean values of 15.2 w-% for forest residues and to 24.5 w-% for SRC, respectively (n = 5, Figure 7). No drying could be observed during container trials for anaerobically stored wood chips.

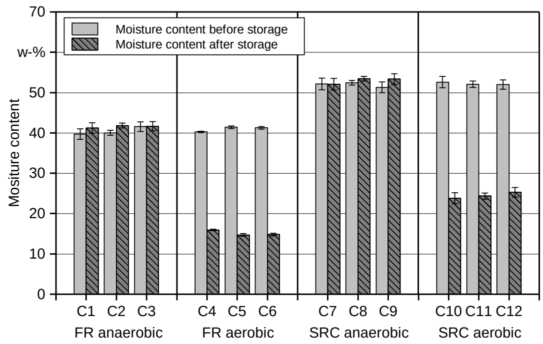

Figure 7: Mean moisture content of wood chips from containers trials before and after storage

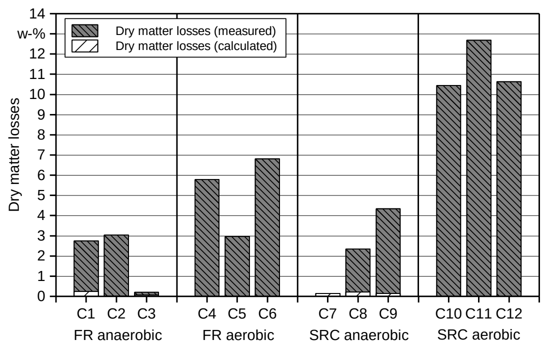

Figure 8: Measured and calculated dry matter losses during container trials

Mean dry matter losses after five months of storage were 5.2 w-% for aerobically stored forest residues wood chips and 11.3 w-% for SRC, respectively (Figure 8). The higher losses in SRC compared to forest residues might be due to higher shares of easily available nutrients for microbial growth in these fuels, but also due to the fact that microbial activity might have occurred longer due to the overall higher moisture content of the SRC fuels at the beginning of storage [2][6]. As a consequence, growing conditions for bacteria and fungi might have been optimal in SRC samples for a longer period of time compared to the already slightly dried forest residue wood chips.

At anaerobic conditions, much lower mean dry matter losses of 2.0 w-% (forest residues) and 2.2 w-% (SRC) were recorded (Figure 8). These results indicate that a depletion of O_2 strongly reduces microbial activity [4][5].

For calculation of dry matter losses, variance in moisture content determination strongly affects the results. Since the total mass did not change for the anaerobically stored variants during storage (see Figure 6), any measured dry matter losses after anaerobic storage seems rather questionable. Previous studies of TFZ and LWF indicated that a variance in moisture content of 1 w-% can lead to a deviation in dry matter losses of 2 w-% [1]. Thus, the observed dry matter losses of the anaerobically stored variant should be much lower, as indicated by the “dry matter losses (calculated)” in Figure 8 using the initial moisture content before storage. The same applies for the aerobic variants but dry matter losses measured for these samples could not be explained by variation in moisture content determination alone, indicating distinct dry matter losses in the aerobically variants due to microbial activity.

Table III: Sampling day, gas volume and concentration of greenhouse gases (GHG) in gas sample bags during anaerobic storage of forest residue wood chips (FR) and wood chips from SRC

Parameter	Day	FR	SRC
Gas volume (l)	2	-	56.4
	7	63.2	65.0
	15	40.5	48.4
CH_4 (ppm)	2	-	0.7
	7	6.1	1.9
	15	7.4	2.3
C_XH_Y (ppm)	2	-	28.9
	7	73.3	35.3
	15	66.7	35.7
CO_2 (vol-%)	2	-	21.5
	7	20.3	24.4
	15	23.4	28.0
CO (mg m^{-3})	2	-	138
	7	186	108
	15	209	56

GHG emissions during container trials indicate a very low microbial activity under anaerobic conditions. Respiratory activity could only be observed during the first 15 days of storage and declined to nearly zero afterwards (Table III), i.e. no further gas could be collected in the gas sample bags. Mean gas volumes measured for the whole storage time was 104 l for forest residue container and 170 l for SRC container, respectively, indicating a higher respiratory activity in SRC. Overall, gas samples were enriched in CO_2 compared to atmospheric values (i.e. 0.4 vol-%) due to respiration by bacteria and fungi [2]. No clear increase in CH_4 compared to atmospheric values (i.e. approx. 1.9 ppm) could be recorded. This might be due to a low activity of methane producing bacteria even under anaerobic conditions. Other authors suggest that the methane that is formed in the anaerobic center of wood chip piles can be reduced to CO_2 by to the activity of methanothrophic bacteria [9]. However, since this requires the abundance of O_2, a general low activity of methane producing bacteria is a much more likely explanation.

Overall, container trials indicated that microbial activity can be supressed under anaerobic conditions and, thus, might be an interesting method to minimize dry matter losses. Ash content and net calorific value did not change during storage. However, even for the anaerobic container some mycelia growth was visible that also might lead to a clustering of individual wood chips. This might have occurred mostly at the beginning of storage when O_2 was still present within the container.

3.3 Storage in small-scale silos

The mean temperature inside the silos was enriched compared to ambient air temperature by 6.8 K for forest residue wood chips and by 9.8 K for SRC wood chips indicating that some microbial activity occurred although the experimental design should facilitate anaerobic storage [1][2][3].

After five months of storage, the total mass of wood chips that was retrieved from each silo was increased in five of six cases (Figure 9). As no wood chips were added to the silos during storage, this effect cannot be attributed to an increase in dry matter but rather to changes in moisture content.

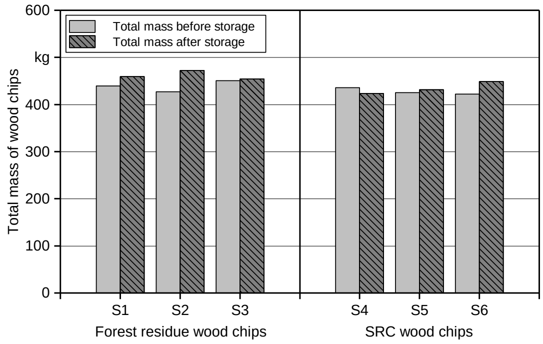

Figure 9: Total mass of wood chips in silos before and after storage

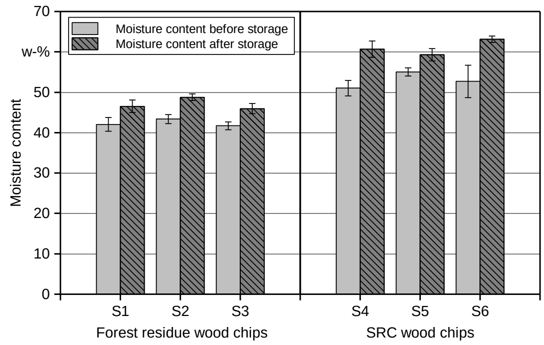

Figure 10: Mean moisture content of wood chips from silo trials before and after storage (n = 5)

In all cases, moisture content in silos increased after storage for approx. 4.2 to 10.4 w-% (Figure 10). As all six silos were stored outside, this indicates that their sealing was not waterproof although a plastic silage foil was used to cover them. Most likely, rain water due to precipitation might have trickled into the wood chip samples between silo wall and silage foil. Moreover, these results indicate that using common techniques to cover silos did not provide for full airtightness for the wood chip silos.

Still, the increase in moisture content alone is insufficient to explain the observed changes in total wood chip mass indicating that at least in five of six silos distinct dry matter losses occurred during storage. These ranged from 3.5 w-% (silo S1) to 22 w-% (silo S4, Figure 11). At the same time, growth of mycelia was visible in SRC silos. Only for silo S2, a negative dry matter loss of 0.8 w-% was recorded. This might be attributed to the effect of a variation in moisture content on the calculation of dry matter losses as it was already discussed for the container trials (see section 3.2).

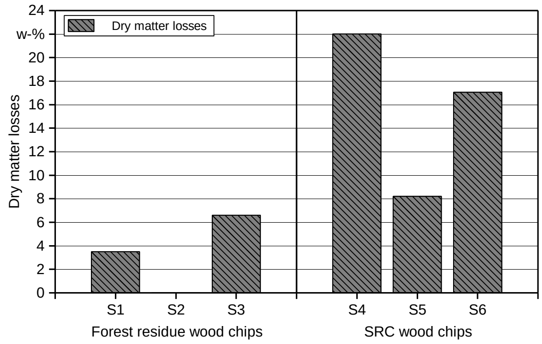

Figure 11: Dry matter losses from silo trials after storage

Overall, the results on anaerobic storage during the container trials could not be replicated using small-scale concrete silos. This was due to the lack of full airtightness under practical conditions. As small-scale silos of 2 m^3 filling volume might be considered the "worst case" for this technique due to a high ratio of surface area to volume, anaerobic storage might be easier facilitated in large driving silos that are common in agriculture. Furthermore, results indicate that airtightness to ensure real anaerobic conditions has to be improved for practical application.

3.4 Small-scale storage pile

Moisture content of wood chips from the storage pile was strongly reduced after five months of storage and mean moisture content was 17.3 w-% (Figure 12). Thus, storage with a fleece cover in a small wood chip pile provided similar drying effects as it was observed for aerobically stored forest residue wood chips during the container trials (see section 3.2) [1][6].

Mean dry matter losses in balance bags were 8.7 w-% and therefore on a typical level for the storage of coniferous forest residue wood chips for five month under Bavarian conditions (Figure 13) [1]. Dry matter losses were higher compared to the storage of the same material in silos (see section 3.3). This indicates that at least some inhibition of microbial activity was present in silos compared to the storage pile and that optimization of this technique might be interesting approach for future studies.

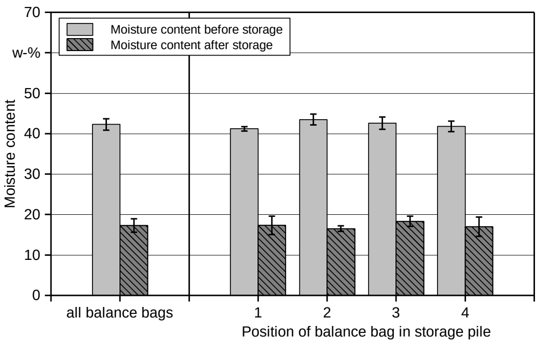

Figure 12: Mean moisture content of balance bags after five before and after storage in a wood chip pile

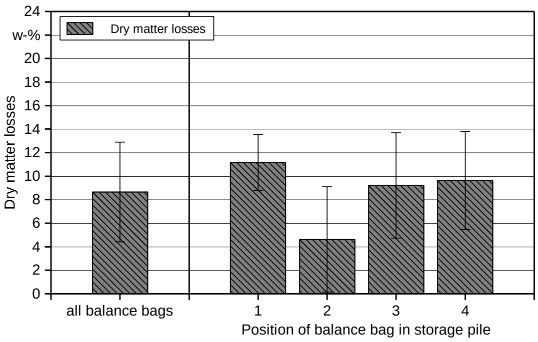

Figure 13: Mean dry matter losses in bilance bags after storage in a wood chip pile

3.5 Combustion trials

Forest residue wood chips from storage trials were combusted in a 30 kW wood chip boiler. Thereby, CO emissions were always below the national emission threshold of Germany (1. BImSchV) for small wood boilers of 400 mg m^{-3} (Figure 14). Still, CO emissions were significantly higher for fuels that were stored in a storage pile compared to wood chips that were dried technically or that were stored in a silo. This effect was also observed for other combustion trials with wood chips from storage piles in previous studies of TFZ.

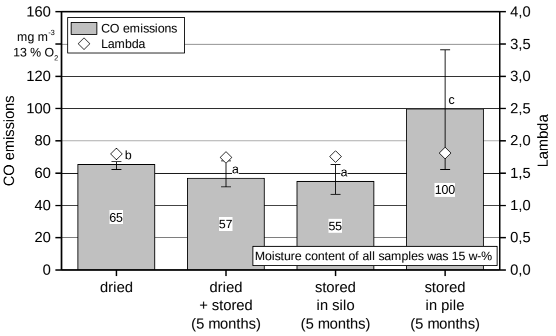

Figure 14: Mean CO emissions during combustion of forest residue wood chips from storage trials in a 30 kW wood chip boiler (n = 5, minor letters indicate significant differences among mean values $p \leq 0.05$)

High CO emissions are always an indicator for incomplete combustion [2]. Since all fuels were combusted at a moisture content of approx. 15 w-%, other fuel parameters might be more relevant for this effect [7]. One possibility might be a difference in energy density per volume of bulk material due to the decomposition of the woody structure by microbes. As a consequence, high volumes of fuel might be necessary to provide for the same nominal heat load, probably leading to overfilling of the combustion chamber and local oxygen depletion [2][10]. Still, the effect of the storage technique on CO emissions was only low.

Mean NO_X emissions were significantly increased during combustion of wood chips that were stored in a silo (Figure 15). However, overall differences in mean values were low. No trend could be observed depending on the N content in fuels [7][10][11][12]. In theory, N content could increase in fuels due to high decomposition of woody biomass during storage [13]. Highest dry matter losses were observed for wood chips from the storage pile. At the same time, N content was highest in the wood chips from the storage pile (0.22 mg kg^{-1} dry basis) followed by the sample from the silo (0.18 mg kg^{-1} on dry basis). Thus, differences in N content fit to dry matter losses but cannot explain the emission behavior regarding NO_X formation.

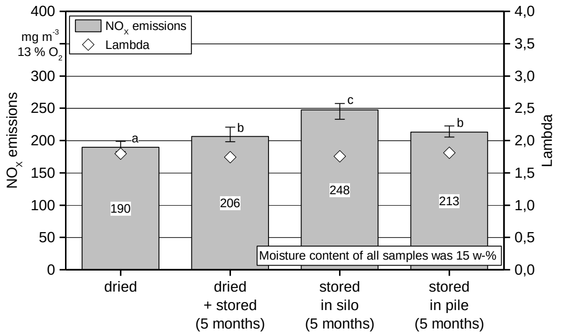

Figure 15: Mean NO_X emissions during combustion of forest residue wood chips from storage trials in a 30 kW wood chip boiler (n = 5, minor letters indicate significant differences among mean values $p \leq 0.05$)

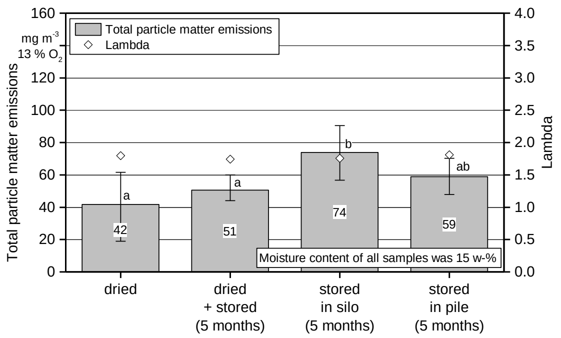

Figure 16: Mean total particle emissions during combustion of forest residue wood chips from storage trials in a 30 kW wood chip boiler (n = 5m minor letters indicate significant differences among mean values $p \leq$ 0.05)

In all cases, total particle emissions were above the national emission threshold of 1. BImSchV of 20 mg m^{-3} (Figure 16). Dust emissions increased significantly during combustion of wood chips from the silo trials. Dust particles derive either by aerosol formation due to the abundance of elements such as K, Na, Pb or Zn or as soot from incomplete combustion [2][7][11][12]. In this study, the fuel sample from the silo trials showed the highest K content (1670 mg kg^{-1} d.b.) followed by the fuel from the storage pile (1440 mg kg^{-1} d.b.) and the technically dried fuels (1040 mg kg^{-1} d.b.). Similar to the N content, K might increase in fuels due to high dry matter losses. Since CO emissions indicated no incomplete combustion for the fuels from silo storage, aerosol forming elements in fuels seem to be the most likely reason for the increased particle emissions [7][10][11].

The results confirm previous combustion trials of TFZ that compared technically dried fuels with wood chips from storage piles. During these trials, wood chips from coniferous forest residues and coniferous energy roundwood were combusted. In both cases, particle emissions were increased during combustion of wood chips from storage piles compared to the technically dried variant, indicating also a negative impact of storage on combustion behavior.

Overall, results indicate that the storage of wood chips in a pile or a silo might lead to slightly increased CO and particle emissions. Especially for particle emissions, this effect might be a challenge to comply with national or European emission thresholds.

4 CONCLUSION

The following conclusions were drawn by the results:

- According to container trials, anaerobic storage of wood chips might be an interesting method to decrease dry matter losses and to conserve fuel quality of fresh wood chips.
- Green house gases (GHG) emerge during storage due to microbial respiration. However, results indicate that the production of methane under anaerobic storage conditions is much lower than expected, probably due to overall low microbial activity under anaerobic conditions.
- For practical application of silo storage, special care has to be taken to provide full air tightness of the silo. This should be facilitated easier in larger driving silos compared to the small-scale trials during this study. When applied correctly, silo storage should lead to much lower dry matter losses and to a preservation of fuel quality (i.e. no drying) compared to the storage in piles.
- During combustion, emissions of CO and particles were slightly increased in naturally stored fuels compared to wood chips that were dried technically. This might be due to changes in their woody structure during storage but also due to enrichment in certain chemical elements.

Overall, anaerobic storage can be an interesting method to decrease dry matter losses but correct application of this technique has to be improved. Further studies should also focus on GHG emissions of larger wood chip piles and on additional combustion trials with stored material.

5 REFERENCES

[1] Hofmann et al., Drying Effects and dry matter losses during seasonal storage of spruce wood chips under practical conditions, (2018), Biomass & Bioenergy, 111, p. 196–205

[2] Kaltschmitt et al, Energy from Biomass, (2016), 3rd. Edition, Springer, 1867 pages

[3] Lenz et al., Open-air storage of fine and coarse wood chips of poplar from short rotation coppice in covered piles, (2017), Biomass & Bioenergy, 83, p. 269–277

[4] Kofman et al., Preservation of forest wood chips, (1999), Fredericia: Elsamproject

[5] Manzone et al., Efficiency of a compactor in wood chip volume reduction, (2015), Biomass & Bioenergy, 80, p. 303–306

[6] Mendel et al., Fuel quality changes and dry matter losses during the storage of wood chips – part 2: Container trials to examine the effect of fuel screening, (2016), Proceedings of 49th FORMEC, p. 135–139

[7] Schön et al. Influence of wood chip quality on emission behaviour in small-scale wood chip boilers, (2019), BCAB, 9, 1, p. 71–82

[8] Kuptz & Hartmann, The effect of raw material and machine setting on chipping performance and fuel quality – a German case study, (2015), IJFE, 26, 1, p. 60–70

[9] Jämsen et al., Measurement methodology for greenhousegas emissions from storage of forest chips–A review, (2015), Renewable and Sustainable Energy Reviews 51, p. 1617–1623

[10] Kuptz et al., Verbrennungsverhalten von KUP-Brennstoffen, (2019), Proceedings of 2. Erfurter Tagung Schnellwachsende Baumarten, p. 52–64

[11] Sommersacher et al, Fuel indexes: a novel method for the evaluation of relevant combustion properties of new biomass fuels, (2012), Energy Fuel 26, 1, p. 380–390

[12] Zeng et al., Impact of adhering soil and other extraneous impurities on the combustion and emission behavior of forest residue wood chips in an automatically stoked small-scale boiler, (2019), BCAB, 9, 1, p. 99–116

[13] Pecenka et al., Influence of the chip format on the development of mass loss, moisture content and chemical composition of poplar chips during storage and drying in open-air piles, (2018), Biomass & Bioenergy, 16, p. 140–150

6 ACKNOWLEDGEMENTS

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7 LOGO

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