CONTAMINATION OF WOOD CHIPS WITH MINERAL SOILS – FUEL QUALITY AND COMBUSTION BEHAVIOUR

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Abstract: *Due to careless operation during fuel production, considerable shares of mineral soil might be added to wood chips leading to contamination of the biofuels. This can result in elevated gaseous and particle emissions, corrosion or slag formation during combustion. To investigate this effect, ten wood chip fuels were partly contaminated with mineral soil or were mechanically upgraded by screening or washing using forest residues of coniferous wood. Contamination was done using three typical forest soils in Bavaria (soil A to C). Total particulate matter (TPM) emissions increased for wood chips that were contaminated with soil A and C compared to the reference fuel, while the emissions for wood chips contaminated with soil B remained constant. For NO_X emissions, no clear trend was detected. CO and OGC emissions decreased for contaminated fuel assortments. Overall, the contamination of woody biomass had a noticeable effect on pollutant emissions and should be therefore avoided.*

Keywords: wood chips, fuel quality, contamination, combustion, emissions

1. Introduction

The contamination of woody biomass with mineral soil might have a substantial impact on the combustion behaviour of the fuels due to an unsuitable chemical fuel composition. Chemical elements that are considered critical for combustion of woody biomass are, for example, nitrogen (N), sulphur (S) and chlorine (Cl). These elements can cause increased emissions of NO_X, SO_X or HCl. Other elements such as potassium (K), sodium (Na), lead (Pb), zinc (Zn) and to a certain degree S and Cl influence the amount of aerosols formed during the combustion process. Chemical elements are also critical in terms of high temperature corrosion (S, Cl) or slagging (K, silicon (Si)) (Dietz, 2016b; Obernberger, 2015; Schön, 2014; Sommersacher, 2012). The concentration of these elements is typically low in wood as they mainly occur in other organic (e. g. needles, bark) or inorganic sources (e. g. mineral soil) (Dietz, 2016b). Due to careless operation during fuel production, high levels of mineral soil may be added to the fuels, e. g. during the logging process, transportation, storage or fuel processing after storage (Kuptz, 2019; Zeng, 2019). Current studies reported up to 10 w-% of mineral soil in woody biomass (Dietz, 2016a). This may lead to unwanted effects during combustion which can even result in a boiler shutdown. Mineral soils in woody biomass could also be an economic disadvantage for the combustion plant operator if the accounting of the delivered fuels is based on fuel mass (Dietz 2016b) or if more ash has to be disposed. Furthermore, soil adhesion to the fuel will also raise mechanical stress in moving parts of the boiler and will thus increase mechanical wear. The aim of this research was therefore to evaluate the combustion behaviour of coniferous wood chips, which were contaminated with 5 and 10 w-% of mineral soil (dry

basis, d. b.). The study included the identification and evaluation of potential damage to boilers (e. g. slagging,) and of the environmental impact (e. g. emissions).

2. Material and Methods

2.1 Selection of mineral soils and wood

The project area was focussing on the state of Bavaria in Germany. Three different types of mineral soil (soil A, B and C) were selected in order to represent large Bavarian forest growing regions of spruce with high wood chip production (Figure 1, left).
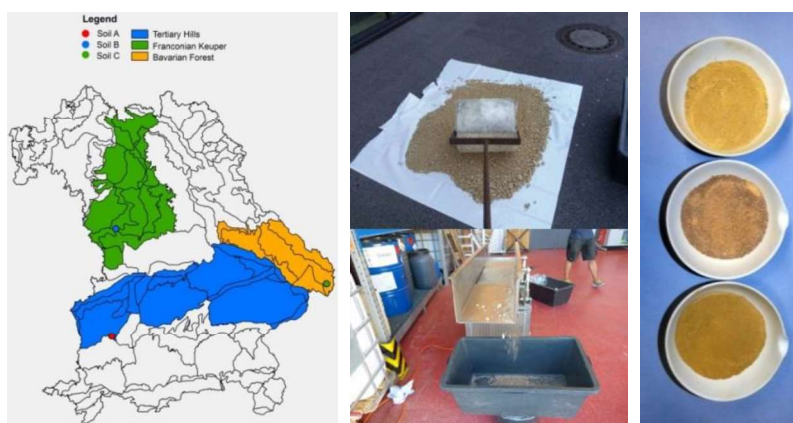

Figure 1: Left: Location of three different soil types. Each soil is representative for the considerable parts of the region (Zimmermann; 2019); centre top: crushing with a concrete roller; center bottom: screening at 2 mm with a self-constructed vibration screen; right, from top to bottom: soils A, B and C;

Forest regions with a high amount of rocks were excluded because contamination with mineral soil is not very likely in these areas. The following soils / regions were selected:

- Soil A: waterlogged loess/clay from tertiary hills
- Soil B: podsol brown soil above sandy-loam Franconian Keuper from northwest Bavaria
- Soil C: brown earth from weathered granite and gneiss substrates from the Bavarian Forest

The mineral soils were taken from the upper 30 cm, excluding the layer of humus. After sampling, each soil was air-dried indoor at room temperature. After drying, each soil was homogenized manually. A representative subsample of every soil was obtained by sample reduction. The respective subsamples were crushed manually using a concrete drum (Figure 1 centre top). The drum was wrapped in cling film to avoid contamination and rolling was done on a tarpaulin. Each soil was then screened mechanically to a grain size of 2 mm using a self-made vibrating screen (Figure 1 centre bottom). This diameter corresponds with the geological fraction-limit between fine soil and coarse soil fraction (Sponagel, 2005). The screened and dried soils can be seen on the right in Figure 1.

The wood fuel was forest residue chips (FRC) of coniferous wood of Norway spruce (*Picea abies*) from the same region as the mineral soil A. Every wood fuel used in the trials was produced from the same raw material batch.

2.2 Mechanical upgrading and washing of wood chips

Three different methods for upgrading the fuel quality were performed on the wood chips prior combustion. Two batches (moisture content: 15 w-%) of wood chips were screened with a self-

constructed drum screen. One fuel portion was screened with a round hole diameter of 8 mm, the second with a round hole diameter of 16 mm. A third fuel portion was washed to reduce mineral soil. The washing was performed following the principle as used in the laboratory method of the BioNorm2-project (Jensen, 2010), but the apparatus was drastically upscaled by constructing a large washing box (1 m × 0.725 m × 0.715 m) of stainless steel. The cover and bottom plate of the washing box is completely formed by a 2 mm round hole screen (Figure 2, left). An IBC tank with removed cover plate was used as a water tank. The fuel portion was washed in three washing steps with 750 liters of tap water by submerging and lifting the washing box into and out of the IBC tank using a fork lift (Figure 2, right).

Figure 2: Washing woodchips; left: washing box with FRC; right: lifting the washing box into and out of the IBC tank;

2.3 Contamination of wood chips with soil

By means of preliminary tests, different types of contamination of wood chips were evaluated. These pre-tests revealed that the best reproducible method was to add the mineral soil to the wood chips immediately before combustion by using a separate dosing screw (Figure 3), which feeds the soil into the horizontal conveyor screw between storage tank and boiler. The dosing screw was placed on a scale to adjust the soil dosing rate in accordance to the desired mixing ratio of soil material and wood chips. Two different contamination levels (5 and 10 w-%) were consistently realized. In total ten different fuel qualities were thus created and tested in the wood chip boiler (Table 1).
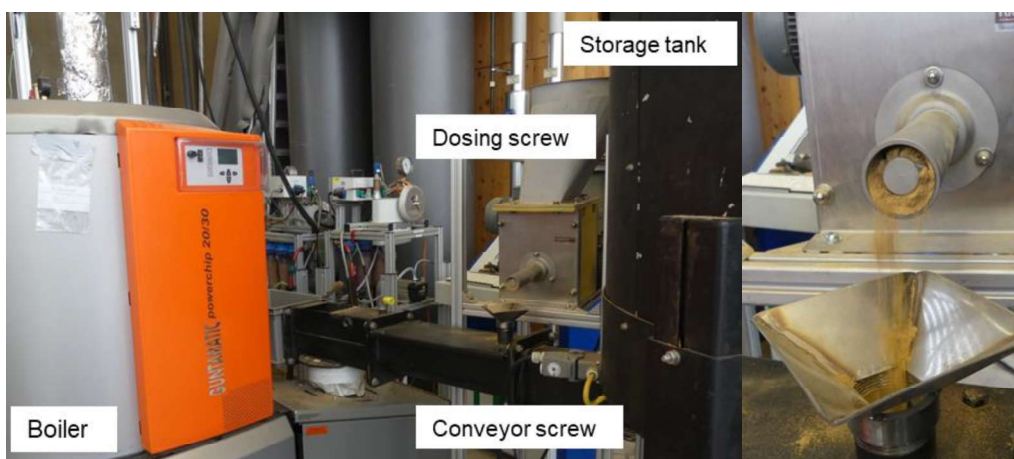

Figure 3: Left: contamination of wood chips with a dosing screw into the screw conveyor. Right: closeup view of dosing screw

Table 1: Nomenclature used for tested fuels

Fuels	Mechanical treatment / contamination
FRC-RS	Reference fuel, no treatment
FRC-W	Washed
FRC-S8	Screened 8 mm
FRC-S16	Screened 16 mm
FRC-A5	5 w - % mineral soil A
FRC-A10	10 w - % mineral soil A
FRC-B5	5 w - % mineral soil B
FRC-B10	10 w - % mineral soil B
FRC-C5	5 w - % mineral soil C
FRC-C10	10 w - % mineral soil C

2.4 Fuel properties

Before combustion, fuel properties were determined according to international standards for solid biofuels. Fuel moisture content was determined gravimetrically according to DIN EN ISO 18134-2 using a drying cabinet (n = 3) (FED 720, Binder GmbH) immediately prior to the combustion tests. Determination of particle size distribution was done according to DIN EN ISO 17827-1. Ash content (n = 3) was determined according to DIN EN ISO 18122 in a muffle furnace (Nabertherm GmbH). Bulk density (n = 3) was determined according to DIN EN ISO 17828 prior to storage. Net calorific value was determined using a calorimeter (C 2000 basic, IKA) according to DIN EN ISO 18125. All chemical analyses were done by a pre-calibrated portable EDXRF device (Epsilon 1, Panalytical). The samples were taken directly from the screw conveyor of the boiler immediately before and after the respective combustion trial, and then homogenised to get a representative sub-sample for the whole batch. For ash content, net calorific value and EDXRF-analysis, the samples were milled to a diameter of < 0.5 mm using a cutting mill (Pulverisette 19, Fritsch GmbH) with heavy metal-free cutting tools. Based on the element concentrations, specific fuel indexes were calculated in order to predict the ash melting behaviour (molar (Si+P+K)/(Ca+Mg)-ratio), the theoretical risk for aerosol formation (Σ(K, Na, Pb, Zn), NO_X-emissions (N-content of the fuel) and K-release (molar Si/K-ratio) (Sommersacher, 2011).

2.5 Test stand and combustion trials

In total, ten different wood chip fuels were combusted (Table 1) in a moving grate boiler (GUNTAMATIC Heiztechnik GmbH, Powerchip 20/30, constructed in 2010) which has a lateral fuel insertion (Figure 4, left). The combustion tests lasted for at least 8 hours including a pre-heating phase lasting for about 2 hours, which was followed by a 6 h full load operation before shutdown. The ash is removed via the moving grate to a screw conveyor which transports the ashes into the ash box. A round storage tank with a flat spring agitator and a screw conveyor was used as fuel feeding systems. To determine the fuel consumption during combustion, the storage tank was placed on a platform scale (Mettler-Toledo GmbH, MT KD600) with a resolution of 0.005 kg. Figure 4 (right) shows a schematic drawing of the test rig and the arrangement of the measurement devices. The heat consumption was permanently regulated to a nominal load of 30 kW 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. The recording interval for the continuous measurement was set to 10 seconds. The total particulate matter (TPM) was measured following VDI 2066-1 applying a filtration temperature of 160 °C during sampling and filter post-treatment. The boiler was operated at constant flue gas draught of -15±2 Pa as it is suggested by the boiler manufacturer. The diameter of the flue gas duct and the connecting pipe was 150 mm. 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 (Figure 4, right). Prior to each trial, the combustion chamber, the heat exchanger and the fuel feeding

system were completely cleaned using a vacuum cleaner, a brush and pressurized air. The storage tank was filled with sufficient amount of fuel and the boiler was started and heated up to steady state operation at nominal load (30 kW) within approx. 2 h. Then the measurements were performed over 6 h at nominal load operation. Within this time period, the gaseous emissions were continuously recorded, but were evaluated only for the duration of the TPM measurements. Five TPM measurements were performed evenly distributed over the whole duration of 6 h each lasting for 30 minutes. All reported emissions refer to dry flue gas at 0 °C and 1,013 hPa and are based on 13 % O_2. All residues of the combustion tests were carefully removed from the boiler and will soon be assessed regarding slag formation.
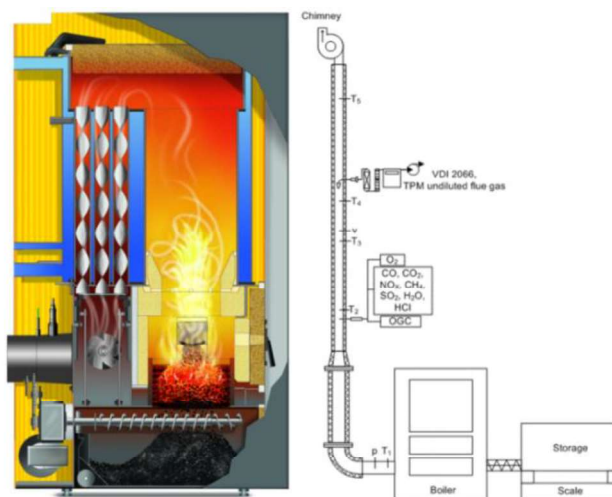

Figure 4: Schematic drawing of the boiler (source: Guntamatic, left) and a schematic drawing of the test stand (right). T1 — T5=temperature measurement points, v=velocity measurement, p=pressure measurement.

3. Results and Discussion

3.1 Fuel properties

The results on physical fuel properties are summarized in Table 2.

Table 2: Physical fuel quality parameters of the produced wood chips
(a. r. - as received, d. b. - dry basis, SD - standard deviation, n. c. — no classification)

Fuel	Moisture content	Bulk density	Ash content	Net calorific value	Particle size distribution	Mineral soil addition
	w-%	kg/m³, a. r.	w-%, d. b. (± SD)	MJ/kg, a. r.	DIN EN ISO 17225-4	w-%, d. b.
FRC–RS	16.48	270	1.95 (± 0.22)	17.97	n. c.	0
FRC–W	15.62	260	1.73 (± 0.15)	17.66	n. c.	0
FRC–S8	14.79	240	1.35 (± 0.27)	17.82	P31s	0
FRC–S16	14.16	240	1.02 (± 0.02)	17.74	P31s	0
FRC–A5	13.13	270	5.35 (± 0.77)	17.64	P45s	3.3
FRC–A10	15.06	280	10.53 (± 0.35)	16.96	n. c.	8.8
FRC–B5	15.00	270	5.13 (± 0.99)	17.58	n. c.	5.0
FRC–B10	15.58	280	9.42 (± 0.31)	17.27	n. c.	8.8
FRC–C5	15.36	280	6.15 (± 0.47)	16.74	n. c.	4.0
FRC–C10	14.93	280	9.40 (± 1.84)	16.52	n. c.	8.6

Due to the previously performed technical drying of all wood chips, the moisture content of the wood fuel used in the combustion trials was in a narrow range between 13.1 w-% (FRC-A5) and 16.5 w-% (FRC-RS). All fuels largely differed in ash content. For the reference fuel, the ash content was 1.95 w-% (d. b.). After mechanical upgrading, the ash content of the washed fuel portion (1.73 w-%) and of the 8 mm (1.35 w-%) and 16 mm (1.02 w-%) screened fuel portion were significantly lower compared to the reference fuel ($p \leq 0.05$, Student's T-Test) due to the reduction of bark, needles or already present impurities in the fuel. At the same time, the ash content of the reference fuel was significantly lower compared to the contaminated wood chips ($p \leq 0.05$, single ANOVA (Tukey)). The actual share of added mineral impurities in the fuels ranged from 3.3 to 8.8 w-% (d. b.). As expected, the ash content of contaminated fuels was in the range of 5.13 to 10.53 w-% (d. b.) due to the addition of inert mineral soil and, thus, much higher than the reference and the mechanically upgraded fuel portions. The bulk densities of the mechanically treated fuel portions were significantly lower compared to the reference fuel due to a higher porosity of the bulk material by removing small particles ($p \leq 0.05$, Student's T-Test). The bulk densities of FRC-B10 and FRC-C5 were significantly higher than the reference fuel ($p \leq 0.05$, single ANOVA (Tukey)). The bulk density of the other contaminated fuel portion was constant or higher. The net calorific value for the reference fuel (17.97 MJ/kg, a. r.) was higher than for all other fuels (16.52 to 17.82 MJ/kg, a. r.) due to no adding of inert material to the fuel (contamination) or due to no separation of fine fuel particles with a predominantly higher net calorific value compared to wood (e. g. bark, needles) by the mechanical treatments. All values of the reference fuel and the washed fuel portions met the requirements of DIN EN ISO 17225-4 fuel class B1. Due to screening, ash content and bulk density were decreased in the fuels FRC-S8 and FRC-S16. Thus, these fuels met requirements of fuel class A2. The contaminated wood chips cannot be assigned to any class of the mentioned standard due to high ash content. The results on the concentration of minor and trace elements and on fuel indexes are given in Table 3 and Table 4.

Table 3: Concentration of minor- and trace-elements in all fuels (d. b. = dry basis)

Fuel	Al	Ca	Cl	K	Mg	Si	P
	mg/kg, d. b.	mg/kg, d. b.	mg/kg, d. b.	mg/kg, d. b.	mg/kg, d. b.	mg/kg, d. b	mg/kg, d. b.
FRC-RS	799	4,529	183	1,518	493	5,125	377
FRC-W	506	4,131	153	1,067	409	3,534	332
FRC-S8	306	3,350	116	1,073	349	1,630	245
FRC-S16	214	2,669	91	977	330	1,063	200
FRC-A5	2,353	3,830	177	1,601	535	10,556	347
FRC-A10	6,024	4,322	179	2,171	600	24,771	384
FRC-B5	1,035	3,837	168	1,417	488	5,319	325
FRC-B10	2,577	4,251	173	1,945	528	10,474	351
FRC-C5	5,037	4,368	159	1,794	592	15,585	355
FRC-C10	5,953	4,256	171	1,933	615	18,368	370

One important fuel index regarding the combustion performance is the ash melting tendency which can be estimated from the molar ratio of (Si+P+K)/(Ca+Mg+Al), the "slagging index". The indexes which are usually used for pure wood fuels and the Al concentration in the soil of the contaminated wood chip might be very high while ash melting temperatures might be increased. With regard to the Al-content of the soils (soil B: 46,630 mg/kg to soil C: 82,220 mg/kg) the (Si+P+K)/(Ca+Mg+Al)-ratio might be preferred for predicting ash melting behaviour of such fuels (Mack, 2019). This index should be low in order to avoid severe slagging (Sommersacher, 2013; Brunner, 2015; Mack, 2019). The index decreases with washing and screening. For contaminated wood chips the index is somewhat higher than for the reference fuel, but differences are not extreme. However, this indicates that slagging problems during combustion of contaminated fuel should be higher in tendency. For every soil the slagging index of 10 w-% contamination is higher than for the 5 w-% variant. A lower ash melting temperature is expected with increasing contamination.

Regarding the K-release, the contaminated wood chip fuels showed distinctly decreased molar Cl/Si ratios compared to reference and to the mechanically treated wood chips. All tested soils have a high

content of Si, so this effect was expected (Brunner, 2015). Thus, the total particle emissions of contaminated fuels were expected to be reduced.

Regarding the part of sum of aerosol forming elements (K and Zn only, since element contents of Na and Pb are too low to be detected by EDXRF) the reference fuel contained 1,561 mg/kg. The mechanically treated fuels are in the range of 977 to 1,073 mg/kg. The contaminated fuels were partly in the same range as the reference fuel and partly considerably higher. Therefore, the prospective total particle emissions from the mechanically treated fuels should be the lowest, followed by the reference fuel and the 5 w-% mineral soil variant. The highest TPM emissions are expected from the 10 w-% contaminated fuels (2,171 mg/kg FRC-A10). Since only two elements are considered, only an initial assessment can be made.

To detect mineral soil in wood chips the Al/200 or Fe/Mn index was used (Dietz, 2016b). If the indexes are > 1, presence of mineral soil is suspected. Following the Al/200 index, every fuel appears to have been contaminated with mineral soil. One explanation might be, that Al is a lightweight element and hard to measure with an EDXRF. On the other hand, there is a clear upward trend in contaminated fuels. So it has to be considered, that the raw material (FRC-RS) has been slightly contaminated with mineral soil from the beginning and therefore a higher Al-content. For further conclusions, the results from the also performed ICP element analyses need to be evaluated (still due). Compared to the Al/200-index the Fe/Mn-index seems in this case better suitable to detect mineral soil impurities. The reference fuel, the washed and the screened fuels are all < 1, while the contaminated wood chips are > 1. One exception is FRC-B5. An increase and partly doubling can be seen by 10 w-% contamination.

Table 4: Fuel indexes calculated for all fuels (d. b. = dry basis)

Parameter	(Si+P+K)/(Ca+Mg+Al)	Cl/Si	Σ (K, Zn)[1]	Al/200	Fe/Mn
	mol/mol	mol/mol	mg/kg. d. b.	mg/mg	mg/mg
FRC-RS	1.4	0.03	1,561	4.0	0.5
FRC-W	1.2	0.03	1,067	2.5	0.3
FRC-S8	0.9	0.06	1,073	1.5	0.2
FRC-S16	0.8	0.07	977	1.1	0.2
FRC-A5	2.1	0.01	1,601	11.8	1.3
FRC-A10	2.7	0.01	2,171	30.1	3.3
FRC-B5	1.5	0.03	1,417	5.2	0.5
FRC-B10	1.9	0.01	1,945	12.9	1.1
FRC-C5	1.9	0.01	1,840	25.2	3.8
FRC-C10	2.0	0.01	1,981	29.8	5.0

[1] Na and Pb cannot be detected by EDXRF

3.2 Combustion trials

3.2.1. Gaseous emissions

CO is the leading indicator for incomplete combustion. These emissions from the use of reference fuel were approx. 134 mg/m³ (Figure 5, left top). Highest CO emissions were recorded for the 16 mm screened fuel with 222 mg/m³. No effect from fuel washing was found. For both screened fuels, CO emissions were significantly increased compared to the reference fuel ($p \leq 0.05$, Student's T-Test). The lowest values were measured using the fuel which was contaminated with 10 w-% mineral soil A (19 mg/m³). All contaminated fuels had lower CO emissions as the reference or the mechanically upgraded fuels (mean $19 - 94$ mg/m³). Thereby, increasing levels of contamination of every soil had a decreasing effect on the CO emissions.

The emissions of the organic gaseous carbon (OGC) are shown in Figure 5 (right top). The highest OGC emissions were detected for FRC-S16 (2.7 mg/m³). The lowest value was measured for wood chips contaminated with 5 w-% of soil A (FRC-A5: 0.3 mg/m³). Washing significantly decreased the OGC

emissions compared to the reference fuel ($p \leq 0.05$, Mann-Whitney-U-Test). For the contaminated wood chips, no clear trend was observed between the 5 or 10 w-% contaminated fuels or the different soils. This was also due to the generally very low level of OGC as it is typical for automatically fed boilers. The values are in the bottom range of the FID.

NO_X emissions were between 187 mg/m³ and 276 mg/m³ on average (Figure 5, left bottom). The highest NO_X emissions were detected for FRC-A10. The emissions decreased with screening compared to the reference fuel ($p \leq 0.05$, Student's T-Test) as needles and bark particles that are generally rich in nitrogen compared to wood were removed. For the contaminated wood chips, no clear trend could be observed between 5 or 10 w-% contaminated fuels or the different soils.
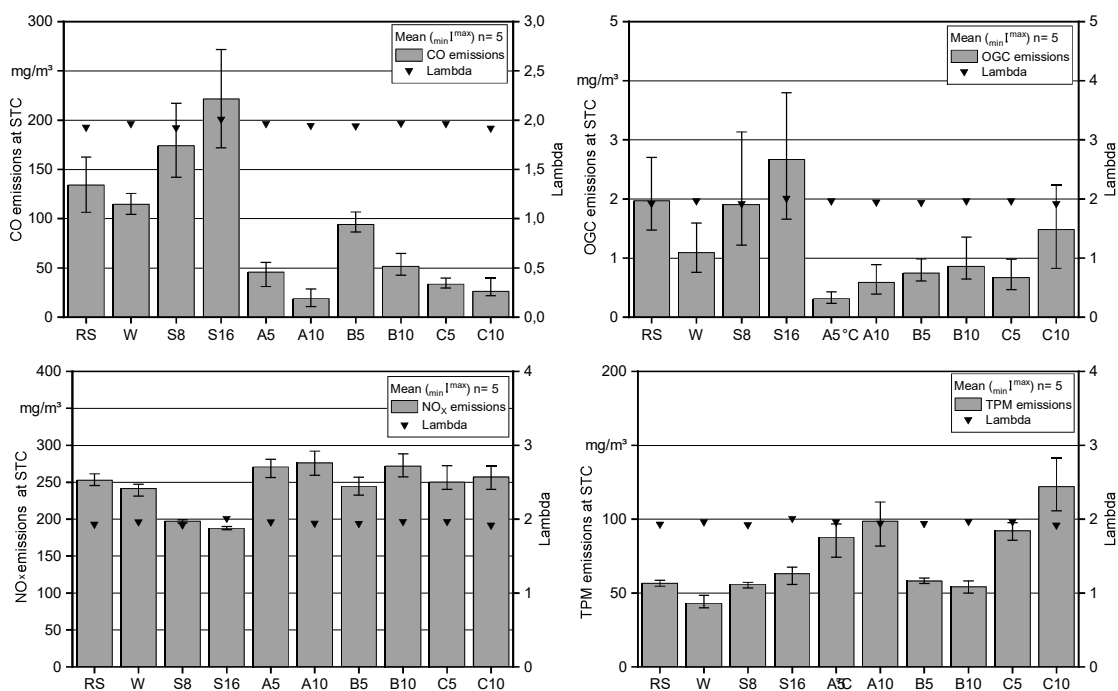

Figure 5: Combustion trials; left top: CO emissions; right top: Org.-C emissions; left bottom: NOx emissions; right bottom: total particle matter (TPM) emissions. Whiskers indicate the range of minimal and maximal values for the measurements. STC = standard test conditions.

3.2.2. Total particulate matter emissions (TPM)

Total particulate matter (TPM) emissions are summarized in Figure 5 (right bottom). The reference fuel led to 58 mg/m³ of TPM during full load operation. These values exceed the German threshold of 20 mg/m³, for TPM emission as defined in the 2nd stage of 1. BImSchV (BMJV, 2010). The highest TPM emission were detected for wood chips contaminated with 10 w-% soil C (122 mg/m³) and the lowest for the washed fuel (43 mg/m³). The TPM emissions of the washed fuel were significantly lower than the reference fuel ($p \leq 0.05$, Student's T-Test) but still above the limiting value of 20 mg/m³. For contaminated wood chips, no clear trend was observed. The emission of FRC-A5, FRC-A10, FRC-C5 and FRC-C10 were higher than the reference fuel. In contrast, the TPM emissions of FRC-B5 and FRC-B10 were on a similar level or lower than the reference fuel. As shown in Table 4, the preliminary index for aerosol forming elements decreases with mechanical treatment. Also the effect of increasing TPM emission for soil A and soil C was also indicated by the index. Regarding the Cl/Si index, the results are indifferent. For further interpretation the ICP values of all elements of the wood chips and the mineral soil need to be seen.

4. Summary and conclusion

The following conclusions can be drawn from this investigation:

- Washing and screening yielded in significantly reduced fuel ash contents, while on the other side the deliberate contamination by soil raised the ash content, as expected. Contamination also showed effect on the calculated fuel indexes which are commonly used for predicting fuel related combustion hazards. Other differences were observed for the concentration of chemical elements in the fuels due to mixing of wood with mineral soil, especially for values for silicon, aluminum and potassium. The highest net calorific value was measured for the reference fuel.
- Washing significantly reduced OGC and TPM emissions while there were no other improvements by washing on CO or NO_x emission compared to the reference fuel.
- Careless operation during fuel production, e. g. during logging, chipping or transportation, might lead to contamination of wood chips and, thus, to problems during combustion. All trials with wood chips that were contaminated with mineral soil resulted in a high amount of boiler ash and, according to the indexes, elevated slag formation is expected (data not shown). The boiler provided 30 kW constant full load operation during every trial. However, severe slagging and too high shares of ash might cause problems for other boilers without a moving grate and can even result in a boiler shut down.
- The CO emissions decrease with addition of mineral soil. No clear trend could be identified regarding NO_X emissions for contaminated wood chips but a reduction was observed for mechanically upgraded wood chips via screening. For CO, the legal requirements of the current national emission thresholds of the German Federal Emission Control Act (1. BImSchV) were met.
- The TPM emissions increased with soil contamination (soil A and C) or remained constant. To date it remains unclear whether this effect is completely caused by thermochemical effects in the fuel conversion process or if it might also be explained by any direct entrainment of soil particles into the flue gas stream.

5. Outlook

Several analyses and trials in the research are still ongoing. The following specific cases and open points will be analysed and published in a scientific paper:
- Complete chemical analyses of the soil and interpretation of chemical reactions in relation to the emissions, including a stoichiometric calculating of the mass fraction.
- Quantification of the ash of the combustion trials, including the amount of slag formation and slag characterization by granulometric analysis.
- Comparison of slagging degree, sintering phenomena and pollutant emissions with fuel indices.
- Combustion trials with energy round wood chips according to the same experimental design.
- Combustion trials with beech and spruce pellets from stemwood in a separate boiler (15 kW).
- Identification of reasons and origin of elevated TPM emissions via particle composition analysis.

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7   Acknowledgments