FUEL QUALITY, STORAGE AND COMBUSTION BEHAVIOR OF NOVEL WOOD FUELS PRODUCED WITH AN INNOVATIVE DUPLEX-SPIRAL CHIPPER

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ABSTRACT: The Effiter 20.30 is an innovative duplex-spiral chipper that produces novel fuels ("Effits") that strongly deviate from conventional wood chips in their particle size, particle form and in their lower share of fines. These fuels might offer advantages during storage, artificial drying and combustion. Five different assortments (whole trees of European poplar from short rotation coppice, stemwood of Norway spruce and European beech, forest residues from hardwood and softwood) were comminuted with the Effiter and a reference drum chipper. During chipping, the Effiter produced coarse particles with a pre-broken structure and significantly lower shares of fines (< 3.15 mm) compared to a conventional wood chips (Effits: 2.1 w-% ± 2.7 vs reference fuel: 4 w-% ± 1.0). The novel chipper reached lower throughput rates in all trials (Effits: 4.0 t_{dm}/h ± 1.8 vs reference fuel: 6.5 t_{dm}/h ± 2.9), as well as higher fuel consumption due to differences in chipper size class. Natural drying during five months of storage performed better with Effits compared to conventional wood chips and dry matter losses were decreased (Effits: 6.5 w-% ± 7.8 vs reference fuel: 11.6 w-% ± 7.0). The Effits showed lower air pressure resistance during artificial ventilation than the reference chips but proved to be more energy demanding on a conventional screw-conveyer. Combustion trials in a 20 kW boiler showed no clear differences in emissions (CO, NO_X, TPM) between the two chipping variants. Overall, the novel fuels produced with the Effiter 20.30 might be an interesting alternative to conventional wood chip production especially for private forest owners with a high fuel quality demand and limited access to artificial drying systems.
Keywords: combustion, drying, chipping, comminution, solid biofuel, wood chip

1 INTRODUCTION

Small and decentralized heating systems that use solid biofuels are an important part of the German heat transition from fossil fuels to renewable energies [1][2]. Especially in rural areas, wood chip boiler< 100 kW are often installed for the purpose of sustainable heat production. Small-scale combustion units have high demands on fuel quality to ensure failure-free, energy efficient, and low-emission combustion. Relevant fuel quality parameters are e. g. a suitable moisture content, a low ash content, low shares of fines and a suitable particle size distribution [3].

In Germany, operators of small-scale wood chip boilers are often farmers or private forest owners that produce their own fuels. Their fuel supply chain is often integrated into their own forest operations and many boiler operators carry out most of the necessary steps during fuel production such as harvesting of the wood, logging, transport, storage, chipping, drying and / or screening of the materials.

During private chipping operations, small and less expensive chippers are often used for comminution. These chippers are usually PTO-driven and are constructed with the aim to produce wood chips with a high and defined fuel quality, especially for combustion in small-scale heating plants. The particle size and particle shape of the produced wood chips as well as the fuel quality in general depend on the raw material, on the skills of the chipper operator and, to a large extend, on the chipping technology [4]. For instance, machine parameters such as chipper type, cut length, knife sharpness, feeding system, output system or the dimensioning of chipper screens of a drum chipper strongly affect particle size and particle form. The same parameters affect fuel consumption and throughput rate during production [4].

Technical innovations might strongly improve energy efficiency and fuel quality during wood chip production and during the subsequent processing steps (drying, storage, combustion). One of such recent developments is the novel and innovative duplex-spiral chipper Effiter 20.30 (Figure 1) of the Bavarian company Alvatec GmbH & Co KG. This system is a small PTO-driven chipper (required power: 40 to 70 kW) that applies two simultaneously operated chipping spirals on the same shaft with opposing screw threads. The shaft rotates at a speed of 270 revolutions per minute. Due to the novel duplex-spiral system, the device does not require a feeding belt or in-feed rollers. The resulting fuels (called "Effits") (Figure 2) differ largely from conventional wood chips in their physical fuel properties such as particle size and particle shape, i. e. they consist mainly of rather large particles with a pre-broken structure and a very low share of fines.

Figure 1: The Effiter 20.30 duplex-spiral chipper powered by a conventional farm machine.

Figure 2. Effits from stemwood of Norway spruce (photo: Tobias Hase, StMELF)

Due to their unique particle form, the Effits promise advantages during drying, storage and combustion compared to conventional wood chips. Thereby, the Effiter 20.30 is especially designed for rural fuel production by local farmers or private forest owners that want to produce high quality fuels for their small-scale boilers.

The aim of this study was to compare fuel production using the Effiter 20.30 with a conventional reference drum chipper of a similar power class. Time studies were applied to analyze chipper throughput rate and energy consumption. The produced fuels were investigated regarding fuel quality, storage stability, transportability in conventional screw conveyors, drying behavior during artificial drying and combustion behavior in a small-scale wood chip boiler.

2 MATERIALS AND METHODS

Five different raw materials were chipped at TFZ during spring 2019 using the Effiter 20.30 and a reference chipper. The materials comprised whole trees from poplar (*Populus maximowiczii*× *Populus nigra*, clone "Max 3") from a three-year old short rotation coppice (SRC), stemwood (diameter from 15 to 30 cm and length of2 m) of Norway spruce (*Piceaabies*) (STW-S) and European beech (*Fagus sylvatica*) (STW-B), as well as mixed forest residues from coniferous softwood (FRC-SW) and from deciduous hardwood (FRC-HW). The nomenclature is given in Table I. An “E” was added to the variants produced with the Effiter 20.30 and a “R” was added to the reference fuels.

Table I: Fuels used during this study incl. abbreviations

Fuel batch	Effiter (E)	Reference (R)
Poplar	SRC-E	SRC-R
Stemwood Spruce	STW-S-E	STW-S-R
Stemwood Beech	STW-B-E	STW-B-R
Forest residues soft wood	FRC-SW-E	FRC-SW-R
Forest residues hard wood	FRC-HW-E	FRC-HW-R

Raw materials derived mainly from forest areas around Straubing (± 70 km) in Lower Bavaria, Germany. For each variant (raw material × chipper), at least 10 to 20 lcm (loose cubic meters) of fuels were produced, generating a total volume of about 120 lcm for all five raw materials. A conventional PTO-driven Heizohack HM 8-400 drum chipper (Heizomat Gerätebau + Energiesysteme GmbH) was chosen as the reference. The model has eight cutting knives, a blower output system, and a maximum in-feed width of 400 x 670 mm. The chipper was equipped with a screen with a hole size of35 × 40 mm. Both machines (Effiter 20.30, reference) were equipped and maintained with sharp cutting knives during all trials. Chippers were operated using the same tractor for each material, i. e. a Kubota M8560 with 67 kW for producing fuels from poplar SRC, stemwood of Norway spruce and both forest residue batches, or with a John Deere 6135R with 100 kW for the stemwood of European beech. All raw materials, except forest residues, were fed into the chippers manually. In the case of forest residues, feeding was performed by crane.

During all chipping operations, time studies were performed to evaluate throughput rate and fuel consumption. Mass and volume of the produced fuel was determined in an agricultural trailer after comminution. The energy demand was determined by measuring the diesel consumption of the tractor using an external fuel tank that was placed on a scale and continuously monitored. After chipping, fuels were sampled representatively according to ISO 18135 and fuel properties were analyzed according to international standards for solid biofuels (Table II).

Table II: Investigated parameters, associated units, and the respective ISO standards

Fuel quality parameter	Unit	ISO standard
Moisture content	w-%	18134-2
Particle size distribution (fine fraction)	w-%	17827-1
Bulk density	kg/m³	17828
Ash content	w-% d.b	18122

Storage behavior and changes in fuel quality during storage were evaluated for all ten fuels in open, small-scale storage containers with a filling volume of approx. 0.6 m^3 (ca. 1100 × 900 × 570 mm). Side walls of the storage containers were insulated using rigid foam insulation panels (30 mm) to create a microclimate similar to large storage piles. All container had a perforated bottom (hole diameter 20 mm) to ensure air circulation. Containers were stored outdoor in a rain and wind protected shelter for 23 weeks. Container mass was determined every 21 days. Previous research projects at TFZ showed that although results from container trials cannot be transferred to outdoor storage piles directly, these containers simulate trends in the storage of wood chips in large storage piles rather well [5].

In addition to container storage, both Effits and the reference fuel of spruce stemwood were stored in an outdoor storage pile of approx. 15 lcm (3 ×5 ×2 m), each, for 23 weeks. Twelve balance bags (approx. 5 l) were filled with sample material and placed into each pile at defined points (pile center, pile surface, etc.) to monitor the changes in fuel quality parameters and dry matter losses over the storage period. The piles were covered with a vapor permeable fleece (PolyTex, Zill GmbH & Co. KG) to avoid rewetting. Temperature profiles were recorded both in the containers and in the piles using temperature sensors (Data logger testo 175-H1, Testo AG; interval: one hour).

Artificial drying was performed directly after the chipping process (Figure 3). All fuels were dried to a moisture content of about 15 w-% in a self-constructed batch drying systems consisting of two containers with a filling volume of approximately 2 lcm each (1650 × 950 × 1320 mm). In this setup, an adjustable blower is used to ventilate the drying boxes from below through a perforated floor with adjustable air flow rates. To improve drying, ventilation air was heated up using an external heater (18 kW). The temperature measurement of the drying air takes place at the entrance of each box. To automatize the drying process, each drying box is equipped with load cells and the drying system shuts down automatically when the calculated target weight (calculated by using initial fuel moisture content and initial fuel mass) is reached. During drying, process parameters of the drying system, i. e. the temperature of the drying air, the drying duration, the volumetric air flow rate (TERZ 94, RMG Messtechnik GmbH, Germany), the changes of fuel mass in each box and the energy consumption of both the blower and the heater were constantly monitored. The efficiency of the drying process is calculated by relating the actual energy used for heating and ventilation to the calculated energy required for the evaporation of the water.

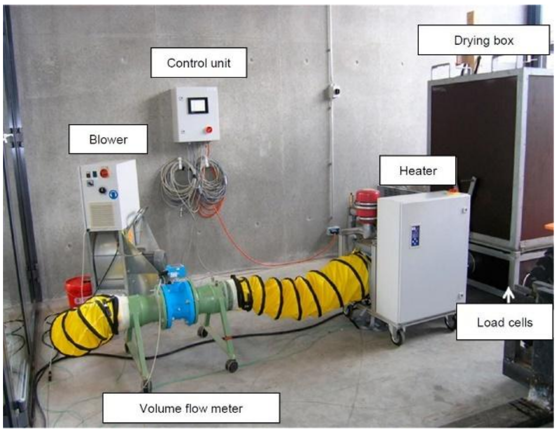

Figure 3: Experimental setup of the batch drying

Air pressure resistance during ventilation was evaluated experimentally in a custom-built flow cylinder. Figure 4 shows a schematic drawing of the test stand.

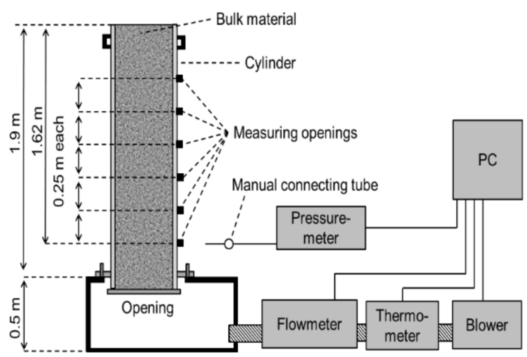

Figure 4: Schematic design of the air pressure resistance test stand used at the TFZ

The cylinder has a height of 2 m and a filling volume of 0.4 lcm. Air pressure resistance (0 to 2500 Pa) was determined by measuring changes in static pressures (P26 (0-100 Pa, 100-500 Pa and 500-2500 Pa) Halstrup-Walcher GmbH, Germany) at six defined positions in the cylinder at varying air flow rates. The air flow was increased in 10 % steps from blower idle (0 %) to 100 %. The airflow was measured continuously (TERZ 94, RMG Messtechnik GmbH, Germany). Each sample was measured twice, whereby the cylinder was emptied and refilled between the experiments. Detailed information on how air pressure resistance was calculated from the data is given in Kuptz et al [6].

Transportability of the dried fuels in screw conveyors of small-scale boilers was tested using a specifically designed test stand at TFZ consisting of a fuel bunker equipped with a conventional screw conveyor (Ø = 100 mm). The test stand was placed on a platform scale (Mettler-Toledo GmbH, MT KD600) and bunker weight was constantly monitored to determine fuel mass flow. Fuel transport was simulated using a dynamic boiler performance cycle. Each conveying test lasted for 80 minutes and conveyor performance was decreased automatically every 8 min from 100 % to 10 % in 10 % steps. The required power of the screw conveyor and thus the total amount of energy as well as exceedances of the nominal power of the conveyor motor were measured in 1 s intervals. Analyses of the particle size distribution and particle form (ISO 17827-1, $n = 1$) was performed for each fuel before and after the trials to identify changes in the physical fuel structure due to the transportation process.

All dried fuels with a moisture content of approx. 15 w-% were combusted in a small-scale wood chip boiler with a thermal output of 20 kW. 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 5 shows a schematic drawing of the combustion test stand and the arrangement of the measurement devices.

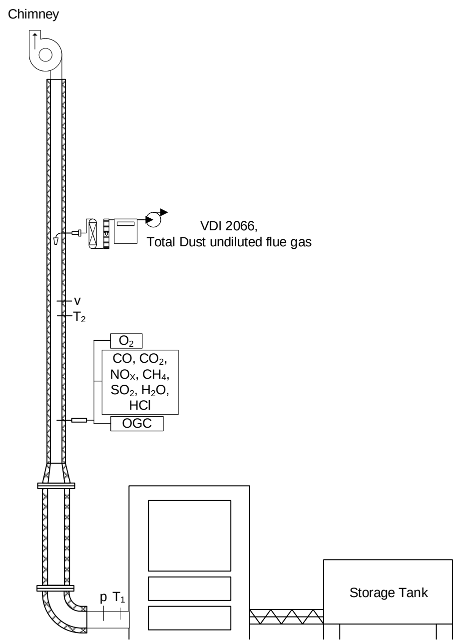

Figure 5: Schematic drawing of the combustion test stand used at the TFZ (position of measurement points: T -= temperature, p = pressure, v = velocity)

The heat consumption was permanently regulated to a nominal load of 20 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, 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 isokinetically sampled following VDI 2066-1 applying a filtration temperature during sampling of 160 °C and the filter pre- and post-treatment temperature of 180 °C and 160 °C, respectively. Also, solid depositions in the sampling line were collected after each measurement day by washing with acetone and subsequent evaporation.

The boiler was operated at a constant flue gas draught of -10±2 Pa as it is suggested 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 80 mm.

For each combustion trial, the boiler was pre-heated to nominal load for approx. 1.5 h followed by a continuous nominal load operation. Five TPM measurements lasting 30 minutes each were conducted within the 5 h operation. After each combustion experiment all ash was removed from the boiler.

If differences between mean values are stated as significant the data was always tested to normality (Shapiro-Wilk) and significance was tested either using t-test or a Mann-Whitney-test. Correlation in data was tested with the Pearson correlation. The level of significance was always set to $p<0.05$. If higher significance levels were reached it is indicated.

3 RESULTS AND DISCUSSION

3.1 Throughput rate and energy consumption

Throughput rate per ton dry mass (t_{dm}) during chipping with the Effiter 20.30 was lower compared to the reference chipper and required a higher amount of energy (Table III).

Table III: Throughput rate and energy consumption during fuel production with the Effiter 20.30 and the reference chipper

Variant	Throughput rate t_{dm}/ h	Fuel consumption L diesel / t_{dm}
SRC-E	2.1	4.4
SRC-R	2.6	3.2
STW-S-E	2.9	4.5
STW-S-R	4.5	2.9
STW-B-E	2.9	6.0
STW-B-R	5.4	3.6
FRC-SW-E	1.6	5.5
FRC-SW-R	2.7	3.3
FRC-HW-E	1.3	5.9
FRC-HW-R	2.1	2.9

The highest throughput rates were achieved during the chipping of stemwood. Approx. 2.9 t_{dm}/h were produced with the Effiter for both stemwood assortments while the reference chipper produced 4.5 t_{dm}/h for Norway spruce and 5.4 t_{dm}/h for European beech, respectively. As the reference chipper is from a larger chipper size class (>100 kW) compared to the Effiter, differences in throughput rate might derive from a generally higher chipping power, but also from the maximal stem diameter of both machines. Chipping with the reference chipper allowed for a maximal stem diameter of 400 mm while with the Effiter 20.30, a maximal stem diameter of 200 mm could be processed. Thus, higher shares of wood could be fed into the reference chipper at a given time interval resulting in the overall higher throughput rates.

In the case of forest residues, both chippers were fed by a crane. The lower throughput rate compared to the manually fed stemwood and SRC wood might thus be related to the crane operation that strongly decreased the feeding rates of the FRC batches. Another reason for the lower throughput rates of FRC might be the much lower mass per volume compared to stemwood so that the feeding operations of the chipper resulted in lower mass input of fuel at a given amount of time. Additionally, the increased bulkiness of FRC wood compared to stemwood due to twigs and branches might cause mechanical resistance during feeding and chipping [4].

The results shown here are related to mass (d. b.). When throughput rates are related to volume, the Effiter still performed lower compared to the reference chipper but the differences were smaller (data not shown). This might be explained by the lower bulk density and therefore the higher bulk volume of the Effits compared to conventional wood chips (see section 3.2), leading to overall larger volumes at comparable fuel masses.

Results on fuel consumption matched results on throughput rates in that the Effiter consistently required a higher amount of fuel per t_{dm}. The differences were most pronounced for forest residues. The data collected show that the difference in fuel consumption of the two machines increases at increasing chipper idle times (e.g. during chipping of FRC batches). This is due to the construction of both chippers. The Effiter, which is driven purely by the torque of the tractor, requires a higher amount of fuel during an idle period compared to the reference chipper, which required less power from the tractor in these periods due to the mass of the chipper drum and the installed flywheel that were already in motion.

3.2 Fuel quality

The moisture content of the comminuted raw fuels was in a range in which microbial activity could still be expected during storage (Table IV) [3]. However, some of the materials were not freshly cut due to the tense precipitation situation and calamity stress, which is reflected in moisture contents between 35 and 30 m-%. These lower values may cause lower dry mass losses. Ash content in the Effits was slightly lower (Table IV). This may be due to lower stem diameters for the materials used in the Effiter and therefor lower shares of bark.

In all cases except for forest residues from coniferous softwood (FRC-SW), the Effits contained a lower share of fines (i. e. particles < 3.15 mm, Figure 6) compared to the respective reference fuel. This effect was strongest in case of stemwood of Norway spruce (STW-S). Here, the average fine fraction in the reference fuel was 36 times higher compared to the Effits (STW-S-E). The significantly lower shares of fines in Effits compared to the reference fuels fits to expectations regarding fuel production in that the Effiter 20.30comminutes the materials in a more cutting motion and at a much lower cutting speed than the reference chipper leading to less breaking of the particles during the chipping process.

Table IV: Fuel quality parameters

Variant	Moisture content	Ash content	Particle size class
	w-%	w-%d.b.	
SRC-E	58.8	1.5	-
SRC-R	58.3	1.8	P31S
STW-S-E	53.7	0.8	-
STW-S-R	55.0	0.7	P31S
STW-B-E	33.3	0.7	-
STW-B-R	37.9	0.7	P31S
FRC-SW-E	36.6	0.7	-
FRC-SW-R	34.0	0.8	P31S
FRC-HW-E	35.5	1.4	-
FRC-HW-R	36.9	2.0	P45S

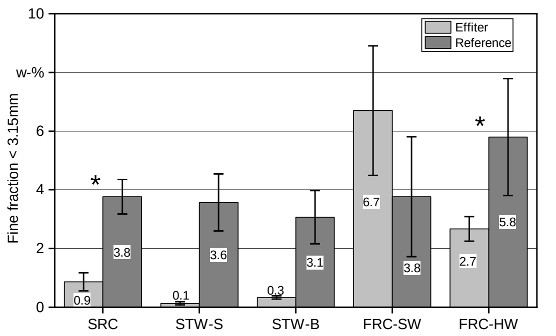

Figure 6: Mean fine fraction (particles ≤ 3.15 mm) in the fuels ± standard deviation (n = 3). * represents significant difference (* p ≤ 0.05; ** p ≤ 0,01; *** p ≤ 0,001) between Effits and reference (t-test and Mann-Whitney-test)

In case of forest residues from softwood (FRC-SW), the fine content of the Effits was higher compared to the reference fuel. In contrast, results on particle size distribution during storage trials (section 3.3) or artificial drying (section 3.4) always displayed lower fines in FRC-SW-E compared to the reference fuel (storage: Effits = 3.5 w-%, reference = 8.0 w-%; artificial drying: Effits = 1.0 w-%, reference = 4.5 w-%). Thus, the here displayed higher fine fraction in FRC-SW-E might be due to unrepresentative sampling of an overall heterogeneous raw material (forest residues) and the relatively small sample size ($n = 3$) for the determination of particle size distribution.

The generally observed higher shares of fine particles in forest residue fuels can be attributed to the higher share of small particles such as needles, leaves or small branches in the unchipped raw materials [4].

Previous studies suggest that a fuel with a low percentage of fines and a high percentage of coarse particles provide for better ventilation during storage and thus for better natural drying (see section 3.4) [6] and advantages during combustion (see section 3.6) [7].

None of the Effits fuels could be classified as one of the particle size classes P16S, P31S or P45S according to ISO 17225-4 while almost all reference fuels were classified as P31S. Only the forest residues reference fuel from hardwood (FRC-HW-REF) was classified as P45S due to overlong particles (thin twigs) (Table IV). Thus, the results on particle size distribution measured by horizontal screening and classification according to ISO 17225-4 suggest that the very large Effits particles might cause problems in the fuel supply system and during combustion in small heating systems. Whether or not this is actually true will be investigated in the following sections focussing on transportability and combustion.

In all cases, mean bulk density (Figure 7) of the Effits (154 ± 25 kg / m^3, d. b.) was significantly lower compared to the reference wood chips (168 ± 29 kg / m^3, d. b.). For SRC-poplar, stemwood from Norway spruce and forest residues from hardwood, bulk densities of the Effits were about 10 kg/m^3 (d. b.) lower compared to the reference fuel while for stemwood of European beech and forest residues from coniferous wood, this difference amounted up to 20 kg/m^3 (d. b.). The lower bulk densities in the Effits are due to their changed particle size distribution, i. e. their higher proportion of large particles compared to the reference fuels. This should result in a higher volume of free air voids in the Effits bulk material and, thus, to a higher porosity of the fuel. Consequently, bulk density is expected to strongly influences process parameters during fuel processing such as air pressure resistance during storage or artificial drying [6].

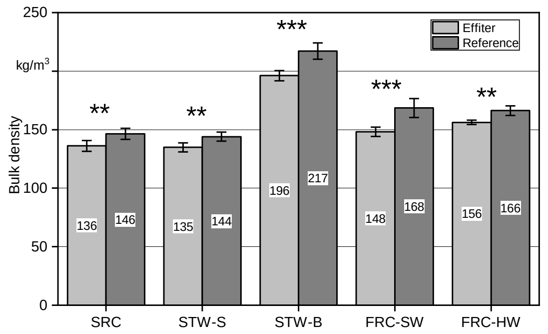

Figure 7: Mean bulk density (on d.b.) for the fuels after chipping ± standard deviation (n = 5). * represents significant difference (* p ≤ 0.05; ** p ≤ 0,01; *** p ≤ 0,001) between Effits and reference (t-test and Mann-Whitney-test)

Highest bulk density was measured for stemwood of European beech. The observed differences among individual raw material were expected due to higher gross density of the hardwood species.

3.3 Storage trials

In most cases, storage of the fuels in containers for 23 weeks led to a strong decrease of the fuel moisture content (Figure 8). Values after storage varied between 16 w-% (STW-B and FRC-SW) and 30 w-% (SRC) for Effits and 18 w-% (FRC-S) and 42 w-% (STW-S) for the reference fuels. In all cases, Effits had a significantly lower moisture content after storage compared to the conventional wood chips ($p \leq 0.05$, t-test) and the reduction in moisture content (ΔM)after 23 weeks of storage due to natural drying in containers was always higher for Effits compared to the reference fuels(Figure 8,Table V).

Four of the five Effits batches from container trials had a moisture content < 20 w-% after storage (Figure 8). Thus, drying in containers was sufficient for the use of these fuels in most small-scale heating systems that often require optimal moisture contents of 15 to 20 w-% for low-emission combustion. For the reference fuels, this was only the case for forest residues from coniferous softwood.

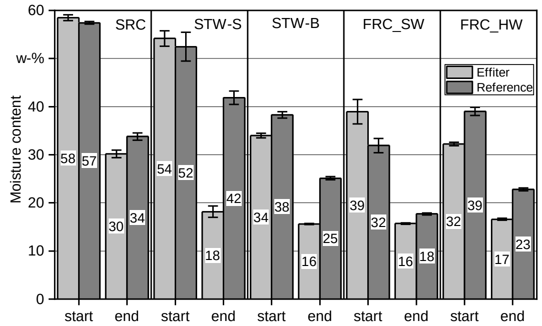

Figure 8: Mean moisture content in the fuels before and after storage in container ± standard deviation (n = 5)

Table V: Reduction in moisture content (ΔM) after 23 weeks of storage in container

Fuel	ΔM w-%	p-value (t-test)
SRC-E	28.3	1.8x10^{-5}
SRC-R	23.6	(significant)
STW-S-E	36.0	1.9x10^{-8}
STW-S-R	10.6	(significant)
STW-B-E	18.4	9.1x10^{-7}
STW-B-R	13.2	(significant)
FRC-SW-E	23.2	1.5x10^{-4}
FRC-SW-R	14.2	(significant)
FRC-HW-E	15.7	0.2
FRC-HW-R	16.2	(not significant)

The monthly dry matter losses in the small-scale storage containers varied between 0.3 w-% (STW-B) and 3.1 w-% (SRC) for the Effits and between 1.1 w-% (STW-B, FRC-SW and FRC-HW) and 4.1 w-% (SRC) for the reference fuel. In all cases, the monthly dry matter losses were 0.8 to 2.6 % lower for the Effits compared to the conventional wood chips. This coincided with higher temperatures (ΔT > 3 K) in the reference containers (data not shown), indicating an increased microbial activity and a lower ventilation within the reference samples [8][9][10].

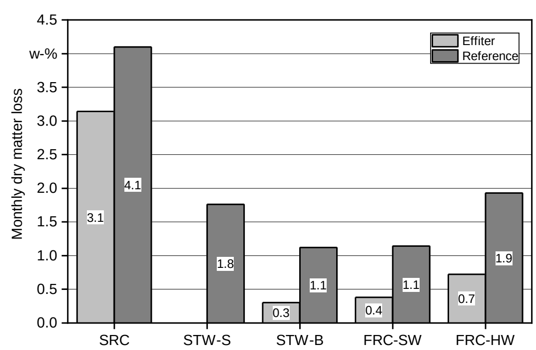

Figure 9: Monthly dry matter loss for the stored fuels, (n = 1)

In case of STW-S, calculation of monthly dry matter loss amounted up to -0.8 w-percent (i.e. dry matter gain) due to calculation uncertainties that results from variation in moisture content determination. Although this value has to be considered illogical and is therefore omitted from Figure, a positive effect of Effits fuels compared to the reference fuels is obvious.

Since some of the fuels showed a moisture content of less than 40 w-% at the start of the storage trials, it can be assumed that the microbial degradation processes and consequently dry matter losses were slightly inhibited during storage. Thus, in fresher materials, monthly dry matter losses might be even higher.

The trend from container trials could be replicated in storage piles, i. e. lower pile temperatures during storage, significantly lower moisture contents after storage (31 w-% vs. 47 w-%; $p \leq 0.05$; t-test) and lower dry matter losses (0.9 w-% vs. 1.3 w-%) for the Effits compared to the conventional wood chips. The moisture content of the fuels after storage in piles was not suitable for an optimal performance of many small-scale boilers. Moreover, fuels from storage piles showed a higher heterogeneity after storage compared to fuels from containers.

3.4 Artificial drying

In contrast to the storage trials, differences among fuel batches during artificial drying were rather small. The calculated efficiency of the self-constructed batch dryer (related to the energy required for drying of fuels from a moisture content of 30 to 20 w-%) is shown in Table VI. Dryer efficiency ranged from 42.56% to 61.72% and was often slightly higher for Effits compared to the respective reference fuels when the same dryer settings (volumetric air flow, heat, etc.) were used for drying.

Table VI: Pressure resistance at an air flow rate of 0.5 m/s and dryer efficiency

Variant	Pressure resistance at a volumetric air flow rate of 0.5 m/s in Pa / m	Dryer efficiency (30 to 20 w-% moisture content)
SRC-E	293	42.56%
SRC-R	464	-
STW-S-E	298	46.73%
STW-S-R	429	46.72%
STW-B-E	255	47.10%
STW-B-R	487	42.15%
FRC-SW-E	488	56.58%
FRC-SW-R	676	54.48%
FRC-HW-E	824	61.72%
FRC-HW-R	686	59.65%

Air pressure resistance (in Pa / m) was strongly reduced during ventilation of Effits compared to the reference fuels in four of five cases (see Table VI and example in Figure 10). The lower air pressure resistance is due to various fuel parameters such as the novel particle structure with its coarse particles and lower share of fines. Particle size and particle form directly influence on the pore volume (i.e. the porosity) and thus the size, structure, and abundance of free air voids within a bulk material. This alters laminar and turbulent air flow through a material [6], affecting both natural and artificial drying. In case of artificial drying systems, process parameters (air flow rate, air temperature, etc.) may be further adjusted to optimized drying by ensuring that the air leaving the dryer is always saturated. This would require considerably more drying trials with constant adaptation of these parameters. Still, based on the results in the air pressure resistance, it can be assumed that the drying of Effits has considerable potential for optimization and that the parameters of the respective drying system should be optimized for the novel fuel.

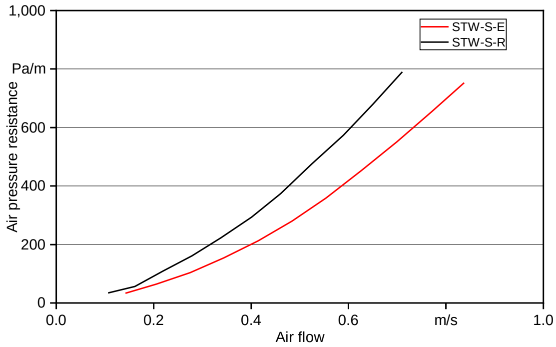

Figure 10: Example for differences in air pressure resistance of Effits and conventional wood chips related to the air flow rate

3.5 Transportability

The transportability of the coarse Effits particles in common screw conveyors of commercially available small-scale combustion systems (screw conveyor Ø = 100 mm) was possible but required a higher energy input and led to a higher number of peak loads that exceeded the nominal power of the conveyor motor compared to conventional wood chips in four out of five cases Table VII). This might result from an increased mechanical stress for conveyor systems during boiler application.

The coarse Effits particles were easily broken down by the conveyor screw due to their pre-broken structure. At the same time, breaking of the coarse particles led to an increase in the fine particle fraction (i. e. particles ≤ 3.15 mm). This resulted in a particle size distribution of the conveyed Effits that was almost identical to that of the reference fuels before fuel transport (data not shown). Thus, no strong differences in emission behavior due to differences in fuel particle size distribution were expected.

Table VII: Performance data of the transportability trials

Variant	Fuel mass(d.b.)	Peaks exceeding the nominal power (550 W)	Maximal power	Energy consumption
	kg	s	W	Wh
SRC-E	126	22	595	334
SRC-R	161	0	455	294
STW-S-E	101	315	844	362
STW-S-R	114	4	595	342
STW-B-E	130	415	878	370
STW-B-R	206	242	812	360
FRC-SW-E	188	13	680	322
FRC-SW-R	192	1	560	316
FRC-HW-E	147	8	743	281
FRC-HW-R	186	161	716	296

3.6 Combustion trials

CO emissions during combustion (at STC, i. e. dry flue gas at 0 °C, 1,013 hPa and 13% O_2)ranged from 55 (FRC-S-R) to 287 mg/m^3(STW-S-R, Figure 11).All values remained below the German emission threshold of 400 mg/m^3 (13% O_2, 1. BimSchV, Step 2) [11]. For some fuels (STW-S, FRC-HW), CO emissions were significantly different when Effits or the reference fuels were applied. However, no general trend between chipping variants could be observed.

High CO emissions indicate incomplete combustion. In this study, CO correlated well with moisture content ($R^2=0.58$) with a significant ($p<0.05$; pearson correlation) correlation. This might be due to cooling of the combustion chamber when fuels with a higher moisture content are applied [3][7]. STW-S-R had one of the highest moisture content (19.9 w-%) and achieved the highest CO emissions during combustion (287 mg/m^3) while FRC-SW-R had one of the lowest moisture contents (11.8 w-%) and the lowest CO emissions (55 mg/m^3) (Table VIII). Thus, the observed differences in CO emissions most likely relate to differences in fuel moisture content rather than to the applied chipping technology.

Table VIII: Moisture content of the fuels after artificial drying and the CO emissions from the combustion trials

Fuel	moisture content w-%	CO emissions mg/m^3 13% O2
SRC-E	22.8	238
SRC-R	18.0	189
STW-S-E	14.6	204
STW-S-R	19.9	287
STW-B-E	11.2	112
STW-B-R	13.4	114
FRC-SW-E	13.7	66
FRC-SW-R	11.8	55
FRC-HW-E	14.6	237
FRC-SW-R	12.0	134

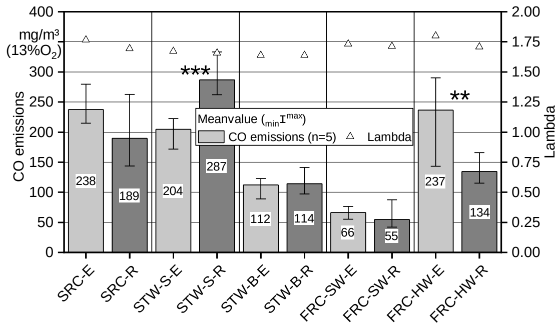

Figure 11: Mean CO emissions (± min/max values) during combustion trials in a 20 kW wood chip boiler ($n = 5$). * represents significant difference (* $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$) between Effits and reference (t-test and Mann-Whitney-test)

NO_X emissions ranged from 148 (STW-S-E) to 336 mg/m³ (FRC-HW-E) (Figure 12). Currently, NO_X is not limited for this boiler class according to German legislation. NO_X emissions strongly differed between raw materials. Significant differences between different chipping techniques (Effits, reference) were observed for SRC, STW-B and FRC-HW but no general trend could be observed.

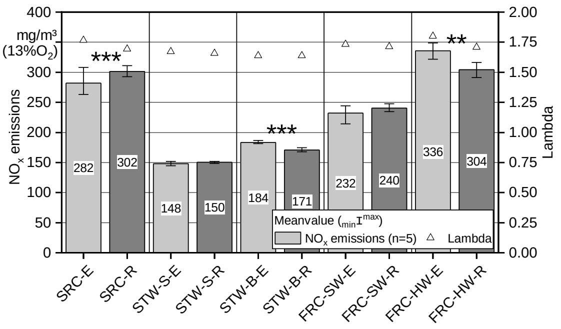

Figure 12: Mean NO_x emissions (± min/max values) during combustion trials in a 20 kW wood chip boiler (*n* = 5).* represents significant difference (* $p \leq 0.05$; ** $p \leq 0{,}01$; *** $p \leq 0{,}001$) between Effits and reference (t-test and Mann-Whitney-test)

NO_x emissions usually can be attributed to N content in fuels [12] explaining the higher NO_X emissions with increasing shares of N-rich plant parts such as bark, needles/leaves and small twigs in FRC or SRC [3] (Figure 12, Table IX). Moreover, the results on elemental analysis show a clear linear and significant correlation between the N-contents of the fuels and the NO_x emissions during combustion ($R^2 = 0.81$; $p<0.001$; pearson correlation). Thereby, N content was lower for many reference fuels compared to the respective Effits, probably due to differences in stem diameter during chipping and therefore due to differences in the ratio of bark to wood.

Table IX: N content of the fuels and the NO_X emissions from the combustion trials

Fuel	N content w-% d. b.	NO_X emissions mg/m^3 13% O_2
SRC-E	0.37	282
SRC-R	0.30	302
STW-S-E	0.12	148
STW-S-R	0.13	150
STW-B-E	0.14	184
STW-B-R	0.13	171
FRC-SW-E	0.36	232
FRC-SW-R	0.19	240
FRC-HW-E	0.56	336
FRC-SW-R	0.39	304

TPM emissions ranged from 10 (STW-B-E, STW-B-R) to 44 mg/m³ (FRC-HW-E). Three of the five raw materials (STW-S, STW-B and FRC-SW) showed TPM emissions below the German emission threshold of 1. BImSchV [11] for small-scale wood chip boilers < 1 MW (i. e. 20 mg/m^{3}at STC) (Figure 13).Significant differences between Effits and reference were measured during combustion of STW-S and FRC-HW but no general trend could be observed.

Schön et al [7] investigated the effect of the fine content on wood chip combustion by mixing woody fines of the same chemical composition to regular wood chips, i. e. by altering particle size distribution but not the share of aerosol forming elements. In their study, TPM emissions increased with increasing fine content. In contrast, no trend could be observed during this study whether Effits (i. e. fuels that are generally low in fines) or the reference fuels were combusted. This might be due to the previously observed breaking of the coarse Effits in screw conveyors and the associated change in particle size distribution / the increase in the share of fines (see section 3.5). Thus, the results indicate that other influences such as moisture content (leading to soot formation due to incomplete combustion), ash content or the amount of aerosol forming elements might be more relevant to explain the observed TPM emission behavior [7].

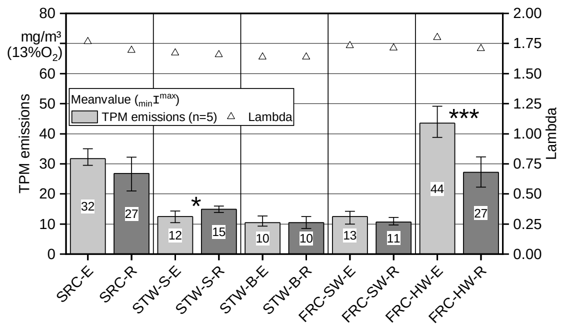

Figure 13: Mean total particulate matter (TPM) emissions (± min/max values) during combustion trials in a 20 kW boiler (*n* = 5).* represents significant difference (* $p \leq 0.05$; ** $p \leq 0{,}01$; *** $p \leq 0{,}001$) between Effits and reference (t-test and Mann-Whitney-test)

Overall, combustion trials indicated that there is no clear trend between the type of comminution (Effiter / reference) and the emissions of CO, NO_X or TPM. During combustion in the 20 kW boiler, no mechanical problems, e. g. clogging of screw conveyors or fuel bridging occurred that could be attributed to the novel structure of the Effits, although these fuels did not met the specifications of any particle size class according to ISO 17225-4. Thus, no improvement but also no disadvantage for combustion could be identified whether Effits or conventional wood chips were applied.

4 CONCLUSIONS

The Effiter 20.30 had lower throughput rates and a higher energy consumption during fuel production compared to the reference chipper. This might be due to different chipper size classes and variation in stem diameters during chipping. Due to the reduced throughput rate compared to industrial scale chippers, the machine might be most suitable for small-scale fuel production, e. g. for farmers or private forest owners that want to produce fuels from their own forests or short rotation coppices.

Fuel production with the Effiter 20.30 resulted in fuels with very low fine contents that had a coarse and pre-broken particle structure compared to conventional wood chips. This led to advantages during storage (better drying, lower dry matter losses) and artificial ventilation (lower air pressure resistance). The novel fuel structure makes the Effiter especially interesting for fuel producers with no access to artificial drying systems, i. e. that want to apply natural drying during pile storage. At the same time, small batch drying systems such as drying containers that are often applied at biogas plants in rural areas usually operate with thicker fuel beds compared to continuously moving dryer (e.g. belt dryer). These small-scale dryers might strongly benefit from the improved ventilation due to the coarse particle structure.

During this study, no clear benefits could be observed regarding artificial drying in the self-constructed batch drying system. However, no adjustments were performed regarding volumetric air flow rate and drying temperature. These parameters might be improved to further adjust the drying process in that the dryer exhaust air should always be saturated. Further trials are required to optimize the drying efficiency of a batch drying system using Effits.

For large scale fuel production, a bigger Effiter size class might be developed. Especially for the setup of industrial scale wood chip storage piles, the duplex-spiral technique might be an interesting approach to improve storage behavior. Further trials are required to test the duplex-spiral technique on storage at a larger scale.

No improvement but also no disadvantage could be observed regarding the combustion behavior of Effits compared to conventional wood chips. This might be due to further comminution of the fuels in small screw conveyors that are commonly used in small-scale boilers. Additional trials are recommended on combustion systems using screw conveyors with a larger diameter or a walking floor, i.e. that do not alter fuel particle structure of the Effits by breaking of the coarse particles. This might lead to reduced TPM emissions during combustion as long as the fine content of the fuels remains low. Moreover, these novel fuels might be especially suitable for combustion in small-scale decentralized wood gas CHP plants that require coarse, high-quality fuels with very low fine contents.

In conclusion, the Effiter 20.30 is an interesting and novel approach for chipping that applies an innovative chipping technique. Currently, it might be considered most suitable for local farmers and private forest owners to supply their own small-scale wood chip boilers, but further fields of application might be developed.

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