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MEETING FUEL SPECIFICATIONS OF EN*plus* WOOD CHIPS BY SCREENING AND DRYING OF FOREST RESIDUES

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Abstract: *To ensure high fuel qualities, the EN*plus *certification scheme for wood chips was lauchned in October 2016 in Germany. Up to date, 15 enterprises are certified. The following study comprises an overview on fuel processing strategies applied by these companies. Moreover, six field trials on screening (drum, star or jigger screens) and drying (storage piles, rolling bed, walking floor, belt and batch dryer) of forest residue wood chips were performed at German biomass terminals. During the case studies, moisture content before processing was too high for small scale boilers (up to 51 w-%). Raw materials did not meet requirements of EN*plus *wood chips (with respect to ash content, particle size). Technical drying provided moisture contents ≤ 15 w-% whereas after natural drying, values usually exceeded 35 w-%. Screening reduced ash content, fines, oversized particles and chemical elements (N, S, Cl, K, Si). After fuel processing, chips could often be classified as EN*plus *specification A2 or B.*

Keywords: fuel quality, screening, drying, ISO 17225-4, EN*plus* wood chips

1. Introduction

Small scale wood chip boilers require homogeneous and high quality biofuels for failure-free and low emission combustion. Especially with regard to emissions and ash formation, fuel properties should be as suitable and homogeneous as possible considering moisture content, ash content, particle size and specific chemical elements (Kaltschmitt *el at.* 2016, Schön *et al.* 2017).

Many fuel quality parameters affect combustion behavior. For instance, high moisture contents often lead to rather low temperatures within the combustion chamber (Buchmayr *et al*. 2015, Quintero-Marquez *et al.* 2014, Kaltschmitt *et al*. 2016). As a result, emissions of CO or soot increase due to incomplete combustion of the fuels while boiler efficiency decreases. High shares of needles, bark material or impurities such as mineral soil due to inappropriate logging operations increase ash content or the content of combustion critical chemical elements (e. g. N, Cl, K, Si) (Kuptz & Hartmann 2015, Dietz *et al.* 2016) leading to high NO_X or aerosol emissions, bottom ash slagging or high-temperature corrosion (Sommersacher *et al.* 2012, Sommersacher *et al*. 2015, Obernberger *et al*. 2015, Zeng *et al*. 2016, Zeng *et al*. 2018). Oversized particles might cause clogging of screw conveyors (Rackl & Günthner, 2016) or increase bridging tendencies (Hinterreiter *et al*. 2012, Jensen *et al*. 2004) of fuels inside storage rooms while high shares of fine particles might hamper combustion air flow through the fuel bed and, thus, also increase particle emissions.

To address uncertainties on suitable fuel qualities, international standards for solid biofuels were developed to provide specifications for different fuel types. In case of graded wood chips, the ISO standard 17225-4:2014-05 specifies 4 fuel classes (A1, A2, B1 and B2, respectively). Thereby, the standard declares suitable raw materials for production (e. g. forest residues, stem wood) but also gives thresholds for fuel quality parameters such as moisture content, ash content, bulk density or particle sizes. These specifications should help fuel producers, boiler manufacturers and customers to orientate on an optimal fuel quality suitable even for small scale combustion appliances. In case of wood pellets, the respective ISO standard is already applied internationally, e. g. by wood pellet certification schemes such as EN*plus* (EPC 2015). In case of wood chips, a similar EN*plus* certification scheme was launched in Germany in October 2016 by the Deutsches Pelletinstitut GmbH (DEPI 2016). Up to date (June 2018), 15 enterprises have been certified.

Fuel quality of natural wood fuels such as wood chips from recently cut forest residues often do not fulfill the specified thresholds of both the ISO standard and EN*plus*. Thus, these fuels are usually not suitable for direct use in small boilers. Secondary fuel processing steps such as screening and drying might strongly improve fuel properties and might help to meet the thresholds set by the wood chip standard. To contribute to a better understanding of scope and limitations of different secondary fuel pretreatment techniques, processing strategies applied by certified wood chip producing enterprises have been examined and field trials on fuel processing with screening and drying have been performed. Thus, the present study aims to (I) reveal optimization potential during wood chip production and (II) to indicate the impact of different pretreatment strategies on fuel quality and composition.

2. Specifications of EN*plus* wood chips

Within the EN*plus* certification program for wood chips, three fuel specifications A1, A2 and B were defined (Table 1). These fuel specifications are directly related to specifications for quality classes A1 to B2 of ISO 17225-4:2014-05. However, for individual fuel quality parameters such as moisture content, fine particles or the maximum particle length, thresholds of EN*plus* are more restrictive compared to the ISO standard.

Table 1: Fuel specifications for EN*plus* wood chips (a = value stricter compared to ISO 17225-4:2014-05)

Fuel property	Unit	EN*plus* A1	EN*plus* A2	EN*plus* B
Moisture content	w-%	≥ 8[a] to ≤ 25	≤ 35	To be stated
Ash content	w-% (d. b.)	≤ 1.0	≤ 1.5	≤ 3.0
Net. calorific value	kWh/kg (d. b.)	To be stated		
Particle size class		P31S or P45S		
Coarse fraction	w-%	≤ 6 in P31S (> 45 mm) or ≤ 10 in P45S (> 63 mm)		
Fine fraction (≤ 3.15 mm)	w-%	≤ 5[a]	≤ 8[a]	≤ 10
Maximum particle length	mm	120[a] (P31S) 150[a] (P45S)	150 (P31S) 200 (P45S)	150 (P31S) 200 (P45S)

For EN*plus*, fuel quality is tested regularly by external auditors. Furthermore, the certified companies are requested to implement a fuel quality management system, e. g. by testing and monitoring fuel quality during fuel production. Other aspects of “EN*plus* wood chips” focus on reliable accounting, e. g. by preferring t (dry basis) over m³, or the application of a complaint management system.

The process chains of all 15 certified enterprises are briefly described in Table 2. Strategies to comply with fuel specifications vary strongly among individual companies. For instance, some companies acquire high quality raw materials (e. g. already dried timber industry residues) while others use screening and drying techniques to improve raw materials with lower qualities such as fresh forest residues. Some entrepreneurs buy already produced wood chips from external sources while others own a chipper themselves. Different methods of screening (drum, star or jigger screens) and drying (natural drying (chipped and unchipped) and technical drying such as batch dryer, rolling bed dryer, belt dryer, etc.) are applied. Finally, process chains differ in the sequence of their process steps, e. g. whether drying is performed before or after screening (Table 2).

Table 2: Process chains used by the 15 EN*plus* certified enterprises (MC = moisture content)

No.	Raw material			Chipper	Fuel processing	EN*plus* class	Particle size class
	Source	Origin	MC				
1	timber industry residues	coniferous wood	dry	no	jigger screen	A1	P31S, P45S
2	stem wood	coniferous wood	fresh	no	star screen - rolling bed dryer with cyclone - jigger screen	A1	P31S, P45S
3	stem wood, forest residues, landscape maintenance	coniferous and deciduous wood	fresh	yes	batch dryer (container) - drum screen	A1	P31S, P45S
4	timber industry residues	coniferous wood	fresh	no	batch dryer (building) with agitator	A1	P31S, P45S
5	stem wood	coniferous wood	fresh	yes	natural drying (unchipped)	A1	P31S, P45S
6	timber industry residues	coniferous wood	fresh	no	batch dryer (container)	A1	P31S, P45S
7	forest residues, landscape maintenance	coniferous and deciduous wood	fresh	yes	jigger screen - batch dryer (container)	A1	P31S, P45S
8	timber industry residues	coniferous wood	fresh	no	jigger screen - feed-and-turn-dryer	A1	P31S, P45S
9	timber industry residues	coniferous wood	dry	no	jigger screen	A1	P31S, P45S
10	forest residues	deciduous wood	fresh	yes	batch dryer (container, only A1), natural drying (chipped, only A2)	A1, A2	P31S, P45S
11	stem wood, forest residues, landscape maintenance	deciduous and coniferous wood	fresh	yes	jigger screen - belt dryer	A1, B	P31S, P45S
12	timber industry residues, forest residues	coniferous wood	fresh	yes	jigger screen - belt dryer	A2	P31S, P45S
13	timber industry residues, stem wood	coniferous and deciduous wood	fresh	no	batch dryer (building)	A2	P31S, P45S
14	stem wood, forest residues	deciduous and coniferous wood	fresh	yes	natural drying (unchipped, only A2), no further processing (only B)	A2, B	P31S, P45S
15	stem wood, forest residues, landscape maintenance	deciduous and coniferous wood	fresh	yes	natural drying (chipped)	B	P31S, P45S

Interestingly, although raw material input and process chains differ strongly, most companies are able to produce high quality wood chips complying with fuel specifications A1 or A2 according to EN*plus* (see Table 2).

3. Materials and Methods

To identify optimization potentials during wood chip production, six case studies on processing forest residue wood chips were performed from December 2015 until May 2016 in Germany (see Table 3). All studies were done at biomass terminals in southern Bavaria with exception of case study 5 which was executed in the east of North Rhine-Westphalia. Raw materials for processing (i. e. samples denoted with an “R”) consisted of forest residue wood chips, mainly from coniferous wood (case study 1, 2, 3, 4 and 6) but also from deciduous trees (case study 5). In most cases, raw materials were obtained directly from forest operations taking place shortly before each case study to ensure high fuel moisture contents. In addition, pre-dried wood chips from storage piles were used as raw materials, i. e. in case study 3b, 5b and 5c. Thereby, due to the overall long drying periods of ≥ 5 month, two different raw materials (R1, R2) were investigated in case studies 3 and 5. The actual process chain of case study 5 consisted of two consecutive screening and drying steps of the same raw material (i. e. steps 1 to 4 in case studies 5, see Table 3).

Fuels were processed by screening (i. e. samples denoted with an "S") using a star screen (case study 1, 2a, 2b 5a, 5b), a jigger screen (case study 1, 6a) or a drum screen (case studies 1, 3a, 3b, 6b) (Table 3). Drying (i. e. samples denoted with a "D") was performed using a rolling bed dryer (case study 1), batch drying container (case study 2a, 2b), a walking floor dryer (case study 4) or a belt dryer (case study 6a). Samples of the final products are denoted with an "E" for "end product".

Table 3: Description of process steps in case study 1 to 6 (Samples denoted with an "R" for "raw material" "D" for drying, "S" for "screening" and "E" for "end product". For coupled processes, i.e. in case study 1 or 6a separating lines were omitted).

Case study	Process step	Sample	Screening / Drying	Process description
1	0 - Raw material	1-R	-	Fresh wood chips (coniferous residues)
	1 - Screening	-	Star screen	Backers (> 28 mm)
	2 - Drying	1-D	Rolling bed dryer	Allgaier WB-T (biogas excess heat)
	3 - Screening	1-E	Jigger screen	SF GmbH ASS 100 (< 1.5mm and < 6 mm)
2a/b	0 - Raw material	2-R	-	Fresh wood chips (coniferous residues)
2a	1 - Screening	2-S	Star screen	Komptech Multistar (> 45 mm and < 20 mm)
	2 - Drying	2-E1	Batch container	Self-constructed (biogas excess heat)
2b	1 - Drying	2-D	Batch container	Self-constructed (biogas excess heat)
	2 - Screening	2-E2	Star screen	Komptech Multistar (> 45 mm and < 20 mm)
3a	0 - Raw material	3-R1	-	Fresh wood chips (coniferous residues)
	1 - Screening	3-E1	Drum screen	Terra Select T3 (< 15 mm)
3b	1 - Drying	3-R2	Pile drying	Pre-dried wood chips (coniferous residues, five month, fleece cover)
	2 - Screening	3-E2	Drum screen	Terra Select T3 (< 15 mm)
4	0 - Raw material	4-R	-	Fresh wood chips (coniferous residues)
	1 - Drying	4-E	Walking floor dryer	Self-constructed (biogas excess heat, screening < 2 mm)
5	0 - Raw material	5-R1	-	Fresh wood chips (deciduous residues)
5a	1 - Screening	5-E1	Star screen	Komptech Multistar (> 45 mm and < 20 mm)
5b	2 - Drying	5-R2	Pile drying	Pre-dried wood chips (deciduous residues, five month, fleece cover)
	3 - Screening	5-E2	Star screen	Komptech Multistar (> 45 mm and < 20 mm)
5c	4 - Drying	5-E3	Pile drying	Pre-dried wood chips (deciduous residues, five month, roof cover)
6	0 - Raw material	6-R	-	Fresh wood chips (coniferous residues)
6a	1 - Screening	6-S	Jigger screen	Zeno P90 (> 45 mm and < 15 mm)
	2 - Drying	6-E1	Belt dryer	Stela (wood CHP excess heat)
6b	1 - Screening	6-E2	Drum screen	Doppstadt 620 (< 15 mm)

For each case study, a full container load of approx. 30 m^3 of wood chips was processed. Thereby, the mass of the unprocessed raw material and of the respective dried or screened products (i. e. wood chips, fine particles, oversized particles) were determined onsite by weighing the whole mass of each fraction using a truck scale of the respective biomass terminal or a crane scale (DINI ARGEO MCW1500, AS Wägetechnik GmbH). Mass fractions were compared on dry basis (d. b.) using the individual moisture content of each fraction (see below).

During each case study, wood chip samples were collected for fuel property analysis. Sampling was done for each raw material and after each process step following ISO 18135:2017-04. Sample preparation was done according to ISO 14780:2017-04. Individual fuel samples were analyzed for moisture content (ISO 18134-2:2015-09, n = 10–20), ash content (ISO 18122:2015-10, n = 3), net calorific value (ISO 18125:2017-04, n = 3), bulk density (ISO 17828:2015-12, n = 10), particle size distribution (ISO 17827-1:2016-03, n = 10) and chemical fuel quality (ISO 16948:2015-05, ISO 16994:2016-07 and ISO 16967:2015-04, n = 1, mixed sample). Afterwards, fuel quality was related to the specifications of EN*plus* wood chips (listed in Table 1).

4. Results and Discussion

4.1. Fuel properties of raw materials

Fuel properties of the unprocessed raw materials were within the usual range for wood chips from forest residues as reported in several studies (e. g. Kuptz & Hartmann 2015, Kuptz *et al.* 2016, Pichi *et al*. 2018, Chandrasekaran et al. 2012, Gendek & Nurek 2016, Spinelli *et al*. 2011). Thereby, mean moisture content of the unprocessed biofuels ranged from 38.1 to 51.0 w-% (samples denoted with an “R” for “raw material”, see Table 4). Thus, moisture content of raw materials usually exceeded the suitable moisture content for small biomass boilers (Schön *et al*. 2017, Kaltschmitt *et al*. 2016).

Table 4: Mean values for moisture content, ash content, net calorific value, bulk density and chemical elements N, S, Cl, K, and Si of wood chip samples in case studies 1 to 6 (mean ± SD).

Sample	Moisture content	Ash content	Net calorific value	Bulk density	N	S	Cl	K	Si
	w-%	w-% (d.b.)	MJ/kg (d.b.)	kg/m³ (a.r.)	w-% (d.b.)		mg/kg (d.b.)		
1-R	41.7 ± 0.8	3.0 ± 0.6	19.2 ± 0.1	310 ± 10	0.32	0.016	66	1,320	5,250
1-D	12.6 ± 1.0	2.1 ± 0.5	19.0 ± 0.1	260 ± 0	0.25	0.013	<54	1,090	1,630
1-E	12.8 ± 1.1	1.4 ± 0.2	19.2 ± 0.1	250 ± 0	0.23	0.010	<58	970	780
2-R	51.0 ± 3.0	7.4 ± 4.2	18.5 ± 0.8	350 ± 30	0.47	0.022	146	1,790	18,750
2-S	52.1 ± 0.7	3.7 ± 1.5	19.0 ± 0.3	360 ± 10	0.35	0.020	126	1,570	8,520
2-E1	3.8 ± 0.2	2.5 ± 0.5	19.3 ± 0.1	220 ± 0	0.33	0.019	94	1,450	5,050
2-R	51.0 ± 3.0	7.4 ± 4.2	18.5 ± 0.8	350 ± 30	0.47	0.022	146	1,790	18,750
2-D	5.5 ± 1.7	2.2 ± 0.7	19.0 ± 0.1	210 ± 0	0.29	0.017	79	1,400	3,720
2-E2	13.1 ± 2.7	1.9 ± 0.7	19.1 ± 0.1	220 ± 10	0.20	0.014	<59	1,170	2,250
3-R1	41.2 ± 3.8	1.3 ± 0.3	18.9 ± 0.1	280 ± 10	0.24	0.010	<56	1,330	690
3-E1	42.9 ± 1.3	1.0 ± 0.1	18.9 ± 0.2	270 ± 0	0.20	0.008	58	1,020	220
3-R2	38.1 ± 6.1	2.5 ± 0.6	18.6 ± 0.1	290 ± 40	0.34	0.016	<56	1,550	5,610
3-E2	38.4 ± 4.2	1.1 ± 0.2	18.8 ± 0.0	260 ± 20	0.25	0.011	<56	1,340	1,170
4-R	42.0 ± 3.0	1.7 ± 0.1	18.8 ± 0.0	290 ± 10	0.34	0.014	<66	1,430	1,630
4-E	7.0 ± 1.0	1.4 ± 0.1	18.7 ± 0.0	200 ± 0	0.30	0.012	<56	1,170	1,020
5-R1	42.5 ± 4.7	3.7 ± 0.2	17.7 ± 0.0	300 ± 10	0.34	0.021	<63	2,380	4,560
5-E1	39.1 ± 0.4	3.0 ± 0.1	17.8 ± 0.1	290 ± 0	0.33	0.017	<57	2,090	2,260
5-R2	41.7 ± 3.7	2.5 ± 0.4	18.3 ± 0.1	300 ± 20	0.32	0.015	67	1,980	3,620
5-E2	32.4 ± 1.2	1.7 ± 0.0	18.2 ± 0.0	260 ± 20	0.23	0.014	<56	1,860	2,080
5-E3	25.2 ± 1.5	2.5 ± 0.4	17.9 ± 0.1	220 ± 0	0.38	0.019	72	2,490	2,560
6-R	48.1 ± 5.2	5.3 ± 1.5	18.5 ± 0.2	330 ± 30	0.36	0.016	<84	2,040	7,380
6-S	48.4 ± 5.1	1.6 ± 0.2	19.0 ± 0.1	-	0.15	0.008	<62	1,300	1,880
6-E1	15.2 ± 2.4	1.8 ± 0.2	19.1 ± 0.1	190 ± 20	0.19	0.008	<87	1,490	1,410
6-R	48.1 ± 5.2	5.3 ± 1.5	18.5 ± 0.2	330 ± 30	0.36	0.016	<84	2,040	7,380
6-E2	45.0 ± 2.3	1.5 ± 0.2	18.9 ± 0.1	290 ± 10	0.21	0.009	<74	1,330	1,020

Interestingly, moisture content of many fresh wood chip samples (i. e. except pre-dried material used in case study 3 and 5) was around 42 w-% indicating that at least some natural drying, e. g. by self-heating of the biofuels due to microbial respiration (Hofmann *et al*. 2017, Lenz *et al*. 2015, Barontini *et al*. 2014) or due to drying during unchipped storage (Routa *et al*. 2015), might have occurred prior to the case studies.

Mean ash contents of raw materials ranged from 1.3 w-% to 7.4 w-% (Table 4). Thereby, highest ash contents were measured for case study 2 and 6, exceeding typical ash contents of forest residues of approx. 3 w-% (Kuptz & Hartmann 2015, DIN EN ISO 17225-1:2014-05). Such high ash contents indicate that some contamination of the samples with mineral soil might have occurred prior to the case studies, e. g. during logging, storage on mineral ground, crane loading operations or transport (Kuptz *et al.* 2016, Dietz *et al*. 2016). In contrast, the lowest ash content of 1.3 w-% in case study 3a indicated a high share of stem wood in the fuel.

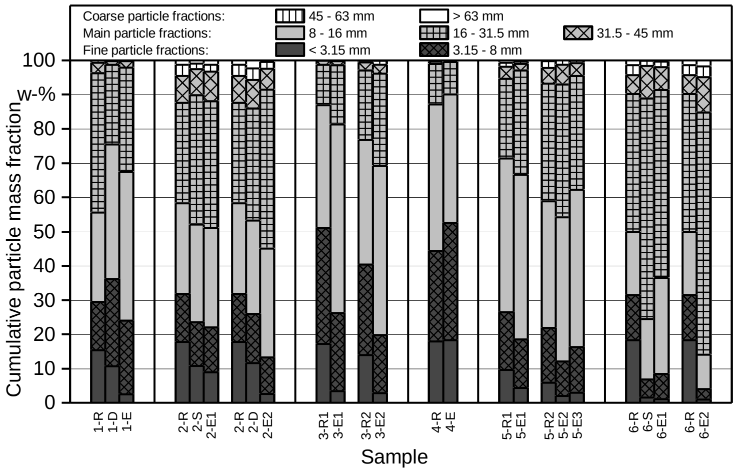

Figure 1: Mean values for particle size distributions of samples in the case studies

None of the untreated raw materials could be classified according to the particle size classes of ISO 17225-4 or EN*plus* wood chips (Table 1) due to high amount of fines (9.6 to 18.2 w-%) or exceeding maximum particle length (153 to 250 mm) (Figure 1). On the other hand, their chemical properties (see Table 4) were within the typical range for forest residues (Kuptz *et al.* 2016). For instance, values for combustion-critical elements such as N, S, Cl or K ranged from 0.24 to 0.47 w-% (d. b.), 0.01 to 0.02 w-% (d. b.), < 56 to 146 mg/kg (d. b.) and 1,130 to 2,380 mg/kg (d. b.), respectively. Moreover, the high concentrations of Si in case studies 2, 5 and 6 (i. e. in samples "2-R", "5-R1" and "6-R", respectively) indicated at least some contamination of samples with mineral soil (Dietz *et al*. 2016).

Overall, the unprocessed raw materials could not be classified according to the EN*plus* specifications A1, A2 or B due to their exceeding ash content or their non-conformity with a specific particle size class.

4.2. Fuel quality after processing

Fuel quality of the raw materials was improved by applying secondary fuel processing (Figure 2, Table 4). Thereby, most fuel qualities of the final products could be classified as either A2 or B quality according to EN*plus* (i. e. in case study 1, 2b, 3a, 3b, 5b, 6a, see Figure 2, Table 1).

Technical drying in case studies 1, 2, 4 and 6 significantly reduced moisture content to levels of 3.8 to 15.2 w-% (Table 4). Thus, after technical drying, most wood chips had a moisture content that is deemed suitable for most small scale boilers (Schön *et al*. 2017, Kaltschmitt *et al.* 2016). To comply with the requirements for the EN*plus* wood chip class A1, however, a moisture content of at least 8 w-% is demanded (Table 1). Too dry fuels below this threshold might lead to an increase in gaseous and particle emission during combustion. Thus, elevated combustion temperatures may lead to a too rapid release of pyrolysis gases which may cause oxygen depletion in the combustion chamber resulting in an incomplete combustion and soot formation. As a consequence, fuels from case study 2a and 4 might be considered "over-dried" and do not comply with moisture content requirements according to EN*plus* class A1. Therefore, to further improve fuel quality, but also the throughput rate of the applied dryer, process chains could be adjusted to moisture contents > 8 w-% (i. e. according to EN*plus* A1, Table 1).

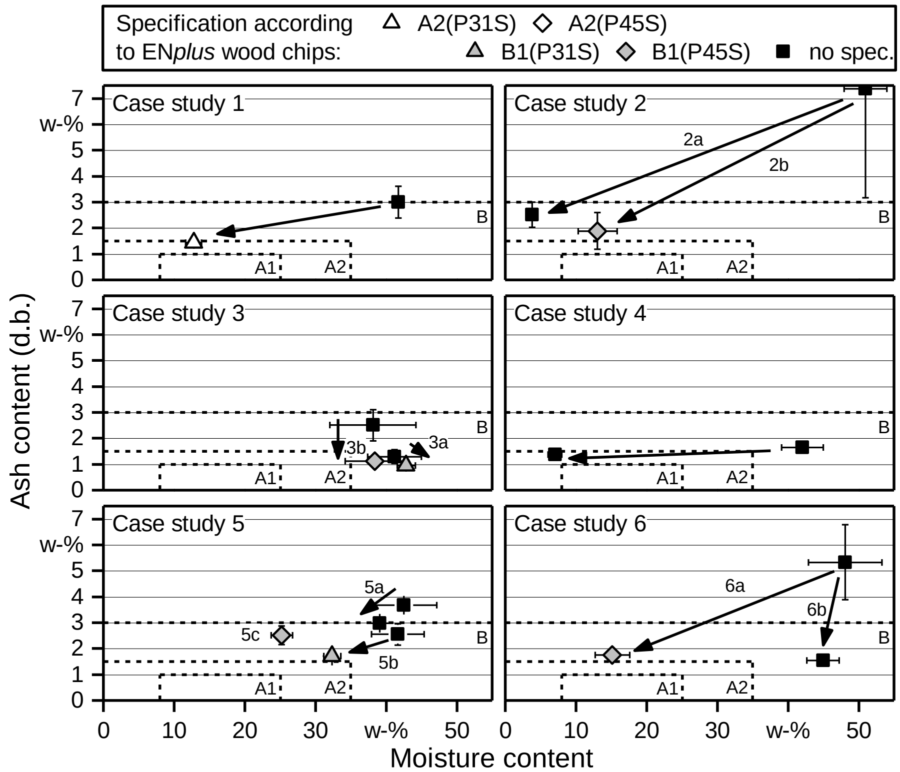

Figure 2: Fuel quality of forest residue wood chips before and after processing in six case studies (mean ± SD, n = 10-20 for moisture content and particle size distribution, n = 3 for ash content). Dashed lines denote thresholds for ash content and moisture content of fuel specifications A1, A2 and B according to EN*plus* wood chips.

In contrast to technical drying, natural drying of wood chips in storage piles did not always lead to a strong reduction in the moisture content during the case studies (see case study 3b, 5b, 5c, Table 4, Figure 2). Drying in storage piles occurs to a large extend due to self-heating of the bulk material during decomposition of organic matter by microbial activity, leading not only to a drying effect but also to dry matter losses between 0.3 and 5.5 w-% per month (Hofmann *et al*. 2017, Lenz *et al*. 2015, Barontini *et al*. 2014, Thörnqvist 1985). Thereby, drying efficiency in piles depends on a variety of factors such as type of the raw material (i. e. tree species, tree compartment, initial moisture content, particle size distribution), the drying season, meteorological conditions during drying, the length of the storage period or the pile covering (Hofmann *et al.* 2018). Unfortunately, no direct conclusion on drying efficiency in storage piles was possible in this study since moisture content could not be determined before and after pile drying due to the long storage periods of approx. 5 months. However, moisture content after 5 month of storage in fleece covered piles still exceeded 35 w-% (case study 3b and 5b). Thus, results from the case studies indicate that natural drying in storage piles for half a year often leads to moisture content levels that are still above the required maximum of 25 w-% (i. e. EN*plus* A1). However, in contrast to the results from the case studies, pile drying is also applied regularly by some of the already certified enterprises (Table 2). Many of these companies produce A1 wood chips. Thus, natural drying in piles as applied in the case studies might be further improved, e. g. by longer storage periods, a change in storage pile design or the use of a different pile covering.

Mechanical screening of raw materials reduced ash contents (case study 1, 2, 3, 5 and 6). Thereby, ash contents decreased to values ≤ 3 w-%, even for raw materials with initially high ash content levels (e. g. case studies 2 and 6). In some case studies, ash content even decreased to values ≤ 1.5 w-% (case studies 1, 3a, 3b, 4, 6b) allowing for wood chips to comply with ash content requirements of specification A2 according to EN*plus* (Table 1, Table 4). Simultaneously, the mass fraction of fines (i. e. particles ≤ 3.15 mm) or of the particle fraction < 8 mm was reduced after screening (Figure 1). As a consequence, particle size distribution of wood chips could be classified as P31S or P45S after the applied screening in many cases due to a decrease of fines and due to a reduction of the maximum particle length (Figure 2).

Ash content and fine particles are interlinked directly as the fine particle fractions usually consist to a large extend of needles, bark particles or impurities such as mineral soil (Dietz *et al*. 2016). These materials have overall higher ash contents compared to stem wood as they contain higher shares of ash forming chemical elements. Moreover, screening not only reduced ash content or fines but also the concentration of chemical elements which are critical for the combustion process such as N, Cl, K, Na or Si. These elements are either relevant for plant metabolism and, thus, elevated levels are typically found in needles and bark, or they are abundant in relevant concentrations within the upper soil layers (e. g. Si) (Table 4). Thus, screening of wood chips can directly improve the combustion behavior and reduce emission of pollutants in flue gas.

The mass fraction of small particles separated from coniferous wood chips by onsite screening was 20.0 to 34.1 w-% (d. b., case study 1, 2 and 6). Lower mass fractions were separated from deciduous wood chips (i. e. 8.8 to 15.0 w-% d. b., case study 5) probably due to the missing share of needles. By using a star or a jigger screen (in case study 1, 2a, 2b, 5a, 5b, 6a), oversized particles could be separated in a range of 1.3 to 14.6 w-% (d. b.). Thus, screening resulted in an overall mass loss in fuels from 23.4 to 35.0 w-% (d. b.) and economically reasonable uses for these by-products should be applied such as bedding for farm animals, composting or combustion in larger CHP plants.

5. Conclusion

Fuel quality in the case studies was typical for wood chips from forest residues. However, untreated raw materials exceeded requirements of EN*plus* wood chips regarding moisture content, ash content or particle size distribution. Moreover, chemical elements implied some contamination of fuels with mineral soil. Thus, the unprocessed wood chips were deemed unsuitable for the use in small scale biomass boilers (< 100 kW).

Similar to the process chains of the 15 certified fuel suppliers, conformity with specifications A2 and B according to EN*plus* could be achieved in many cases during field trials by screening and drying. However, in the case studies the highest specification A1 was never achieved. Further processing of the fuels but also the use of different raw materials (e. g. stem wood) or the use of different machine settings might be necessary to achieve this quality. If wood chips should be combusted in small scale boilers, technical drying seems preferable over natural drying in storage piles. However, “over-drying” (e. g. case study 2a and 4) should be avoided to optimize fuel quality and throughput rate in the drying step.

To increase the overall economic efficiency of the case studies, a high annual capacity for the screening machine and the dryers should be achieved. Furthermore, suitable utilizations for by-products after screening, i. e for the small and oversized particle fractions, are required such as bedding for farm animals, composting or combustion in larger CHP plants as 23.4 to 35.0 w-% (d. b.) of the fuels were removed during processing.

In conclusion, during the performed field trials, secondary fuel processing steps such as screening or drying were a suitable option to improve fuel quality of wood chips. Afterwards, fuel quality complied with fuel specifications according to EN*plus*. Thus, the production of high quality wood chips can be guaranteed by applying these techniques, leading to fuels that should allow for failure free and low emission combustion even in small scale boilers.

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