Dichrostachys cinerea as a possible energy crop – Facts and figures

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ORIGINAL ARTICLE

Dichrostachys cinerea as a possible energy crop—facts and figures

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Abstract Biomass contributes already with more than 10% to cover the global energy demand. This contribution will continue to grow in the years to come due to increasing fossil fuel prices and climate protection. To make this happen, additional sustainable biomass resources must become available to be used as a source of energy. Against this background, the goal of this paper is it to analyse the properties of *Dichrostachys cinerea* (Marabú) as an energy crop. The investigation shows that this wood is characterised by properties comparable with other types of woody biomass with a longer crop period. Only the ash content is slightly higher. In addition, the airborne emissions released during combustion are relatively low in general. Thus, wood from *D. cinerea* (Marabú) can be seen as a promising fuel.

Keywords *Dichrostachys cinerea* · Energy crop · Airborne emissions

1 Introduction

All in all, the global energy demand will increase substantially in the years to come. However, there are regional differences. While the energy demand of the industrialised countries will remain more or less stable, the demand of the emerging economies as well as developing countries will increase significantly. For example, the increase in coal consumption in China between 2008 und 2010 has been in the range of the overall coal consumption of the European Union.

For this reason, there is an urgent need to develop alternatives for a technically mature, economic feasible and environmental sound energy provision. The use of solid biofuels as an energy carrier is such a promising alternative market mature since centuries. However, to expand the use of biomass significantly in a sustainable way, additional biomass resource needs to be exploited. One possible alternative is the use of plants that grow fast and out of control, even on degraded land (i.e. not on land used for agricultural purpose), having a negative impact on the local ecosystem (e.g. they are not native) and have no commercial use in most cases.

The plant *Dichrostachys cinerea* (Marabú) is such a plant. For example, this invasive plant pollutes Cuba significantly. According to the latest census, Marabú grows on more than 1.25 Mio. ha (i.e. 20% of the Cuban arable land) or 12% of the national territory [1]. In addition, there is basically no special use for this plant.

Against this background, the goal of this paper is it to investigate the properties of *D. cinerea* (Marabú) as a solid biofuel and to draw some conclusions about the possibilities to use this biomass as an energy carrier. To reach this goal, first the Marabú plant is described and the investigated sample is presented. Afterwards fuel and combustion-related properties of this plant are analysed and discussed.

2 *D. cinerea*

D. cinerea is a semideciduous to deciduous tree. This plant is commonly known as the Sicklebush, Bell mimosa, Chinese lantern tree or Kalahari Christmas tree (South Africa). In Cuba, this tree is named as Marabú.

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The plant is characterised by bark on young branches, dark grey–brown fissures on older branches and stems as well as smooth on the spines. This tree typically grows up to 7 m in height and has strong alternate thorns, generally up to 8 cm long. Flowers of the *D. cinerea* are characteristically in bicoloured cylindrical spikes that resemble Chinese lanterns. They are 6–8 cm long and fragrant. Upper flowers of a hanging spike are sterile. They are of a lilac or pale purple. Pods are usually mustard brown and are generally twisted or spiralled. Figure 1 shows a schematic diagram of this plant [2, 3].

The Marabú tree grows in tropical areas in altitudes up to 2,000 m. This plant can be found often in areas with a strong seasonal climate with a wide-ranging mean annual temperature and with an average annual rainfall ranging from 200 to 400 mm. The tree occurs in brushwood, thickets, hedges, teak forest and grassland. Generally, the plant takes poorer quality clay soils or deep and sandy soils [2, 3]. This plant fixes atmospheric nitrogen and is a soil improver.

D. cinerea penetrates clear-cut areas far into the rain-forest zone. For example in Malaysia, this crop can be found in areas with strong seasonal climate usually on poor, occasionally clayey soils, in brushwood, thickets, hedges, teak forest and grassland. It can be an indicator of overgrazing in low rainfall areas.

Usually, this plant is not frost resistant. The tolerance is less on poor soils. Nevertheless, this plant is definitely drought resistant. It is fire resistant and does not tolerate water logging [2]. It is difficult to eradicate as it shoots again from portions of root. In certain situations, mechanical or chemical control measures are the only ways to control the potentially serious weed.

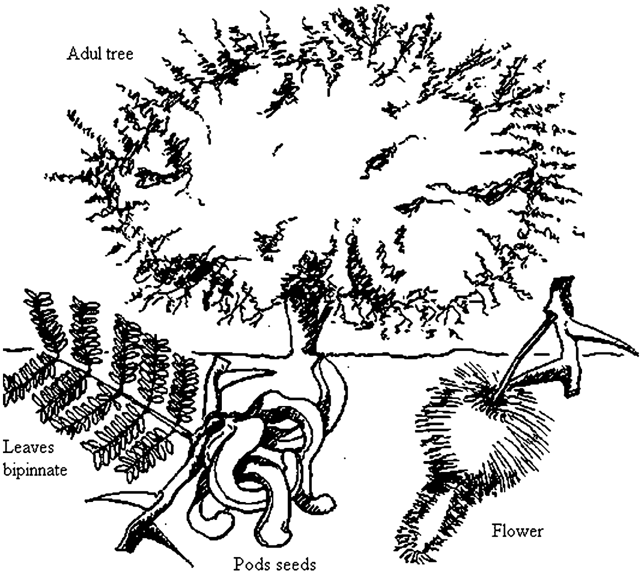

Fig. 1 Schematic *D. cinerea* [25]

3 Investigated sample

The experimental investigations realised here have been carried out based on a piece of Marabú wood removed from stem wood with a diameter of approximately 5 cm. This piece of wood originates from the plains of the western region of the island of Cuba in the province of Pinar del Rio. This plain has a height less than 100 m above sea level.

This stem has been cut in October 2010 from a fully developed tree with a height of approximate 4 m; afterwards, the sample has been stored for several months in a dry place (i.e. with humidity below 50%) at room temperature (20–35°C) to reduce the water content in wet basis, from 44% when the samples were collected, to 8.4% when the analysis were carried out.

This sample has been prepared using the standard methods for sample preparation for solid biofuels [4]. This method ensures that biases are avoided in reducing the initial size of wood fuels down to small samples of consistent size for repeatable laboratory measurements. Care must be taken to minimise moisture loss during the reduction process before a total moisture sample is weighed.

A key quantity determined during solid fuel preparation is the loss on air drying to determine the moisture loss when a crushed sample is equilibrated in the laboratory atmosphere before grinding it to a powder. To allow for realistic results, the original mixture between wood and bark have been kept assuming that for an energetic use, only the thicker parts of the tree branches are used and the thinner parts (below 2–3 cm) are left on the production site to improve the soil quality by increasing the humus content.

4 Fuels properties

To understand the properties of Marabú as a solid biofuel, the fuel properties have been analysed applying different methods defined within the respective standards (Table 1). Below the different types of fuel properties analysed here are described in detail.

4.1 Proximate analysis

Within a proximate analysis (Table 2), the fractions of volatiles, ash and fixed carbon are determined. The latter is obtained by subtracting from 100% the sum of volatile matter and ash content in percentage. Table 2 shows the results.

According to Table 2, roughly 19% of the Marabú biomass consists of fixed carbon. Additionally, close to 79% of the overall biomass is volatile matter. The overall ash content is between 2% and 2.5%.

Table 1 Analytical methods employed

Property	Analytical method
Calorific value	DIN CEN/TS 14918
Moisture content	DIN CEN/TS 14774-1
Ash content	DIN CEN/TS 14775 DIN 51719
Volatile	DIN CEN/TS 15148
Ultimate elemental (C, N, H and S)	DIN CEN/TS 15104
Cl, F and S	DIN CEN/TS 15289, DIN EN ISO 10304-2
Ash elemental	DIN CEN/TS 15290, DIN 38405, DIN EN ISO 17294-2

These measured values for the Marabú samples are in the order of magnitude reported by other literature sources [5]. In the case of the share of volatiles, the measurements presented here show a little lower values compared to the values indicated in [5] (i.e. ca. 79% compared to 81% published in the cited study). Beside this, the values of ash and fixed carbon are slightly higher here compared to the figures published in [5] (i.e. 1.5% [5] vs. 2.3% (Table 2) for the ash content, 17% [5] vs. 19.2% (Table 2) for the volatiles). One reason for these differences could be the fact that the composition of the plant material is influenced by the soil and climate conditions to certain extent. In addition, the samples for the investigation cited above have been collected in the eastern part of the Cuban island, where the weather is slightly different to the western part. This might explain the differences beside the fact that the precision of the measurements could be different.

If the results of the proximate analysis are compared to other types of biomass (Table 2), the following observations can be made.

- The content of volatiles of Marabú is a little bit lower compared to other herbaceous or woody biomass (Table 2); but this value is in the same order of magnitude.
- The ash content is slightly lower in comparison to sugarcane bagasse and higher compared to other woody biomass characterised by a longer growing period. The content of noncombustible material within Marabú is very much within a range typically found also within other types of biomass.
- The amount of fixed carbon is higher compared to the other types of biomass investigated here. Marabú shows the highest fixed carbon value of all the plant species reported in Table 2. Nevertheless, it is within an order of magnitude typical for biomass.

4.2 Ultimate analysis

Based on an ultimate analysis, the elemental composition of the Marabú is determined. Here, the fractions of carbon, hydrogen, nitrogen, sulphur, chlorine are measured with an accuracy level of ≤0.3% and a precision of ≤0.2% according to the specification of the measuring device [6]. The ash is measured with the same accuracy and precision level [7]. Additional errors (e.g. during sampling, inattention of the lab assistants) add to this error level. Based on these values, the share of oxygen is calculated by difference. Table 3 shows the measurement results.

The measurement results show that Marabú consists to more than 49% of carbon (C) and roughly 42.5% of oxygen (O). Hydrogen (H) contributes with slightly more than 5%. All other elements investigated here (N, S, Cl) are clearly below 0.5%.

According to Table 3, Marabú can be classified within the other types of biomass as follows.

- The C content of Marabú is relatively high. Compared to other plants investigated here, it is surpassed only by poplar wood. Nevertheless, the carbon content within Marabú wood is more or less in the order of magnitude usually found in biomass.
- The H content of Marabú is comparable with the content reported for the sugarcane bagasse. However, it is lower than the content reported for woody biomass. Nevertheless, this value is within a value range typically found in biomass.
- Marabú as a plant is able to remove N from the air. This could be one reason for the higher concentration of this element in the Marabú wood compared to the other types of wood shown in Table 3. The nitrogen content of the woody biomass from Marabú is in the same order of magnitude as the herbaceous biomass wheat straw.

Table 2 Results of the proximate analysis for the Marabú sample and comparison with other types of biomass (wb with bark)

	Marabú (wb)	Sugarcane bagasse [26]	German beech (wb) [27] in % dry fuel	Fir (wb) [27]	Poplar (wb) [27]	Wheat straw [26]	Rice straw [26]
Fixed carbon	19.23	11.95	15.50	16.50	17.00	17.71	15.86
Volatile matter	78.90	85.61	84.00	82.90	81.20	75.27	65.47
Ash	2.35	2.44	0.50	0.60	1.80	7.02	18.67
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 3 Results of the ultimate analysis for the Marabú sample and comparison with other types of biomass (wb with bark)

	Marabú (wb)	Sugarcane bagasse [27]	German beech (wb) [27] in % dry fuel	Fir (wb) [27]	Poplar (wb) [27]	Wheat straw [26]	Rice straw [26]
Carbon (C)	49.250	48.64	47.900	49.800	47.500	44.92	38.24
Hydrogen (H)	5.380	5.87	6.200	6.300	6.200	5.46	5.20
Nitrogen (N)	0.440	0.16	0.220	0.130	0.420	0.44	0.87
Sulphur (S)	0.060	0.04	0.015	0.015	0.031	0.16	0.18
Chlorine (Cl)	0.035	0.03	0.006	0.005	0.004	0.23	0.58
Oxygen (O) (*diff.*)	42.480	42.82	45.200	43.200	44.100	41.77	36.26
Ash	2.350	2.44	0.500	0.600	1.800	7.02	18.67
Total	100.000	100.00	100.000	100.000	100.000	100.00	100.00

- The content of sulphur (S) and chlorine exceeds the values found for the other types of biomass shown in Table 3. Nevertheless, these values are within a range more likely to be found in herbaceous and not in woody biomass.
- The O content is relatively low compared to the other types of biomass (Table 3). Nevertheless, the values are within an area typically found in biomass.

4.3 Ash composition

Table 4 shows the elemental composition of the Marabú ashes. This includes six elements in the organic phase and other elements in the inorganic phase. Sulphur accounted for as an element in the ultimate analysis and as sulphate in the ash analysis.

Following the data outlined in Table 4, the following observations can be made.

- Marabú ash consists mainly of calcium (Ca). Compared to this element, all other components are of minor importance.
- Elements contributing with a noticeable amount are iron, magnesium, phosphorous, S and silicon (Si). Together with Ca, these elements are responsible for clearly more than 90% of the ash content.
- The other elements analysed here are only of minor importance related to the overall ash composition. Worth noticing are the alkali and earth alkali metals. The primary sources of possible problems related to these metals are (1) the reaction of alkali with silica to form alkali silicates that melt or soften at low temperatures and (2) the reaction of alkali with sulphur to form alkali sulphates on combustor heat transfer surfaces.

Compared to other types of woody and herbaceous biomass [8, 9], these values are very much in the same order of magnitude. Therefore, the ash composition of Marabú does not show any significant irregularities.

4.4 Calorific value

The standard measure for the energy content of a fuel is its calorific value. Table 5 shows the gross and net values determined according to the method outlined in Table 1 with precision of ≤0.1% RSD.

According to Table 5, the calorific values measured for Marabú wood are very much similar to the calorific values of the other types of biomass shown in this table. This woody biomass is characterised by a calorific value comparable to other woody crops and slightly higher compared to herbaceous biomass.

4.5 Alkali index

The alkali index expresses the quantity of alkali oxide within the fuel per unit of fuel energy ($\mathrm{kg_{Alkali}/GJ}$). Although this index is incomplete as an overall descriptor of slagging and fouling behaviour, it gives useful hints for assessing the behaviour of a certain type of biomass as a fuel. Experiences have shown that above 0.17 $\mathrm{kg_{Alkali}/GJ}$ fouling is probable

Table 4 Results of the ash elemental composition of the Marabú sample (on dry basis)

Al	31.10 mg/kg	Cr	1.91 mg/kg	Li	0.182 mg/kg	Ni	1.64 mg/kg	Zn	12 mg/kg
Ba	5.09 mg/kg	Co	0.093 mg/kg	Mg	874 mg/kg	Si	324 mg/kg	W	0.491 mg/kg
Pb	1.03 mg/kg	Fe	225 mg/kg	Mn	13.6 mg/kg	Sr	54.4 mg/kg	P	338 mg/kg
Cd	0.02 mg/kg	K	67 mg/kg	Mo	0.026 mg/kg	Na	60.9 mg/kg	S	760 mg/kg
Ca	6,768 mg/kg	Cu	2.46 mg/kg						

Table 5 Results of the calorific values for the Marabú sample and comparison with other types of biomass (wb with bark)

	Marabú (wb)	Sugarcane bagasse [27]	German Beech (wb) [27]	Fir (wb) [27] in MJ/kg	Poplar (wb) [27]	Wheat straw [26]	Rice straw [26]
Gross calorific value	19.84	17.32	20.2	19.7	19.8	17.94	15.09
Net calorific value	18.69	15.84	18.8	18.4	18.5	16.53	12.82

and above 0.34 kg_{Alkali}/GJ fouling is virtually certain to occur [8]. These threshold levels are determined based on experience and may thus vary considerable. Table 6 shows the values determined here based on the data outlined above.

Thus, Marabú wood show a low value of the alkali index compared with other types of woody biomass. The alkali index of this type of biomass is similar to the value for fir and sugarcane bagasse. The latter is remarkable considering the fact that bagasse is subjected to a leaching process during the juice extraction procedure. Following these values, no major problems with slagging and fouling are expected during combustion of this fuel.

5 Combustion behaviours

The combustion behaviour of Marabú is important for the design of a combustion devise fuelled with this type of biomass to allow for high overall conversion efficiencies. Additionally, the fuel properties influencing significantly the airborne emissions regulated in one way or another in most countries especially in large-scale plants [9]. For these reasons, emissions formed during the biomass combustion process are intensively investigated [10–14].

To get an estimate about the combustion behaviour of Marabú wood in comparison to another wood types, trials has been carried out within an experimental device according to Fig. 2. Because the fuel characteristics as well as the combustion behaviour of German beech wood (*Fagus sylvatica*) is well-known in literature as well as in practice, this wood has been chosen as a comparative value (Table 7).

German beech wood is one type of wood most commonly used in Europe as a source of energy. German beech is a large tree that may reach heights [15] of up to 49 m and 3 m trunk diameter. More typically, in "classical" managed forests the tree grows up to 25–35 m and shows a trunk diameter of up to 1.5 m. This tree has a typical lifespan of 150–200 years. The appearance varies according to its habitat. Under forest conditions, it tends to have a long, slender light grey trunk with a narrow crown and erect branches. If the tree grows in isolation with good side light, the trunk is short with a large and widely spreading crown with very long branches. The fuel properties of this wood are reported in "Fuels properties" section.

Table 6 Alkali index for the Marabú sample and comparison with other types of biomass (wb with bark)

Marabú (wb)	0.08 kg_{Alkali}/GJ
Sugarcane bagasse [26]	0.06 kg_{Alkali}/GJ
Fir (wb) [26]	0.06 kg_{Alkali}/GJ
Willow wood (wb) [26]	0.14 kg_{Alkali}/GJ
Poplar (wb) [26]	0.14 kg_{Alkali}/GJ
Wheat straw [26]	1.07 kg_{Alkali}/GJ
Rice straw [26]	1.64 kg_{Alkali}/GJ

The flue gas compositions is measured with the Gasmet FTIR CX-4000 analyzer [16] with a Peltier cooled (MCT) detector and a resolution of 4 cm^{-1} with 10 scans/s. FTIR is used in demanding emission measurements since it is a robust, sensitive, fast and continuous measurement technique.

The concentrations are measured from wet flue gases and the data is collected in 9 s intervals. Heatable lines heated up to 180°C are used to prevent condensation of the flue gas compounds inside the tubing and the measurement device. The temperature in the base of the oven is also recorded.

The simplified experimental setup is presented in Fig. 2. According to this, the combustion process takes place in an oven with a cubic form (edge 0.75 m). An extractor fan placed on the top of the oven supplies the combustion air. The flue gas and the oven temperatures at the base of the combustion chamber are recorded with an interval of 5 s. For one test run, 0.73 kg of wood samples (with bark) is used.

The oven is heated up before the experiment is started by the combustion of wood until a temperature of 1,073 K (i.e.

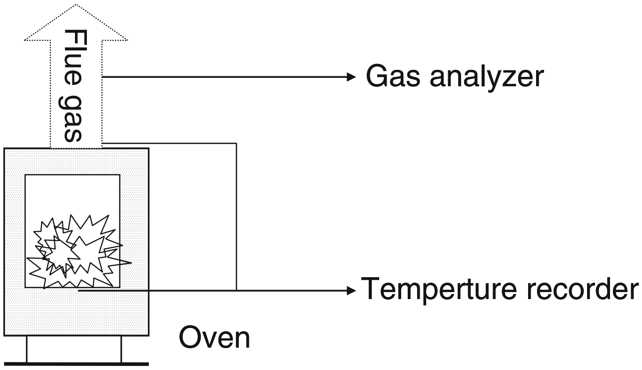

Fig. 2 Scheme of the experimental setup

Table 7 Technical data of the measuring devices

Element	Gauge/manufacturer	Measuring principle	Measuring range	Maximum uncertainty
CO_2	Gasmet CX 4000 FTIR/Ansyco	Fourier transform infrared absorption	0–12.5 vol.%	0.4 vol.%
H_2O			0–12.5 vol.%	0.4 vol.%
CO			500–8,000 ppm	165 ppm
NO_x			0–200 ppm	2 ppm
SO_2			0–200 ppm	2 ppm
O_2	PMA 100-L/M&C products	Paramagnetism	0–21 vol.%	0.3 vol.%
Hydrocarbons	Thermo-FID/Mess-and Analysentechnik GmbH	Flame ionisation	0–100 ppm	4 ppm
			100–1,000 ppm	39 ppm
			1,000–10,000 ppm	394 ppm
Temperature	Thermocouple (type N)/Philips Company-Thermocoax	Thermoelectricity	0–1,570 K	±2.5 K

800°C) is reached in the base of the chamber. Then the rest of the combusted wood is removed and the sample wood to be studied is placed in the oven. This sample is then completely combusted. The measurements achieved with this experimental setup are discussed in detail below.

5.1 Combustion behaviour

The combustion behaviour of a wood sample can be described by the temperature distribution during the full thermo-chemical conversion as well as with the formation of the most important combustion products (i.e. carbon dioxide (CO_2) and water (H_2O)). Both aspects are discussed below.

Figure 3 shows the oven temperature measured during a combustion experiment with a Marabú wood and a German beech wood sample. Thus, the maximum temperature achieved during the combustion of beech wood is 1,301 K. During the combustion of Marabú, a temperature of 1,128 K has been measured under similar conditions. Both temperature maxima have been reached roughly 85 s after the experiments has been started with less than 5 s difference. The medium combustion temperature for the Marabú wood sample is 181.6 K lower than the average combustion temperature for the Beech wood sample. The observed variation of temperature in both cases occurs at a very similar rate with oscillations that are observed in the vicinity of the same temporal moment in both experiments. This is a strong indicator that the experimental conditions do not vary much resp. the wood fuel characteristics are in a comparable range.

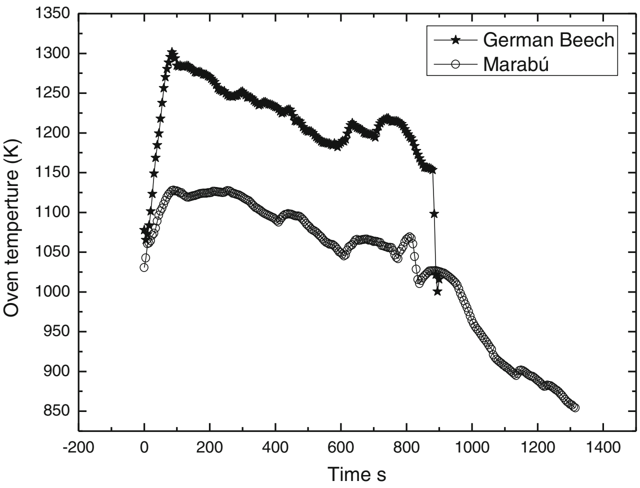

Fig. 3 Measured oven temperature for the two samples

The conversion rate of the woody biomass to gaseous volatiles and solid residual char can be modelled as first order reactions in terms of the residual mass of the biomass components together with an Arrhenius approach for the solid temperature influence. According to this, the reaction rate is low and the conversion time is long at low temperatures. This is an explanation why the time required for the total combustion of Marabú is ca. 47% longer than the total time required for the beech combustion (Fig. 3).

The faster combustion measured for the German beech wood in comparison with the Marabú wood sample is also correlated with the formation rate of the main products of this thermochemical conversion process, namely CO_2 and H_2O. The respective values measured during the combustion experiments are shown in Fig. 4

The maximum formation of CO_2 and H_2O is observed approximately at the same time in both cases (i.e. when the maximum temperature is reached in the oven).

Even due to the differences outlined above, the two wood samples analysed here show basically the same behaviour. This similar picture can again be explained by the comparable fuel properties.

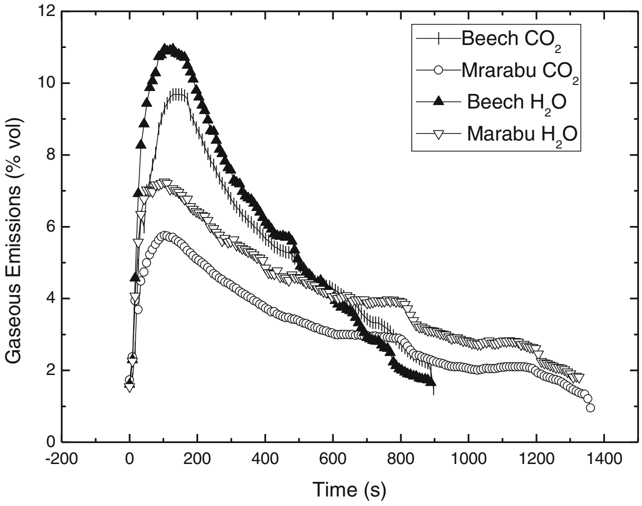

Fig. 4 CO_2 and H_2O formation during combustion experiments of the two samples

5.2 NO_x emissions

Usually, gaseous nitrogen compounds (i.e. NO_x with the components nitrogen oxide (NO) and nitrogen dioxide (NO_2)) are emitted during biomass combustion to certain extends. These emissions are harmful to the environment due to their acidification potential and their contribution to an anthropogenic nitrogen input into natural ecosystems via the atmosphere. For these reasons, in most countries, the release of NO_x emissions from combustion units into the atmosphere is limited.

During combustion, NO_x emissions are formed through different pathways known as thermal NO_x, prompt NO_x and fuel NO_x [17–19]. Thermal NO_x and prompt NO_x are formed at high combustion temperatures from nitrogen introduced into the thermochemical conversion with the combustion air. Therefore, these two formation pathways do typically contribute only to a minor share to the NO_x emissions released from biomass combustion units because the temperatures needed for their formation are hardly reached in such devices. This is not necessarily the case for fuel NO_x. This NO_x emission provision pathway is based on the nitrogen contained within the biofuel [20]. Therefore, the following rule of thumb is usually valid: the higher the nitrogen content in the fuel the higher the NO_x emissions. According to this, higher NO_x emissions are expected from Marabú wood compared to German beech wood.

The production of NO and NO_2 can be described by the two basic Eqs. 1 and 2.

$$N_2 + O_2 \leftrightarrow 2\,NO \tag{1}$$

$$NO + \frac{1}{2}\,O_2 \leftrightarrow NO_2 \tag{2}$$

During combustion, the two reactions (1) and (2) are performed simultaneously. At ambient temperatures, reaction (2) is likely to take place and any NO formed is converted to NO_2. At higher temperatures, reaction (1) proceeds with a major probability. This is the reason why under these circumstances the concentration of NO exceeds the concentration of NO_2.

Thus, at conventional combustion temperatures (>2,500 K), NO formation is possible with negligible amounts [17, 18] of NO_2.

Following these basics, significantly higher NO emissions are expected to be measured from the combustion trails of the two different types of wood.

Figure 5 shows the NO and Fig. 6 the NO_2 emissions measured during the two experiments described above.

According to Fig. 5, the measured emissions of NO are clearly higher for the Marabú wood compared to the beech wood. Thus, the measurements confirm the theory because the nitrogen content within the Marabú wood is almost twice its content in the beech wood and, according to the measured temperatures (Fig. 3), the fuel NO_x formation pathway should dominate the overall NO_x formation.

Figure 6 shows the NO_2 emissions measured during both experiments. On a first glance, there are no significant differences in the concentration behaviour of NO_2 between the two wood types. The measured NO_2 emissions are rather low in absolute term as well as compared to the NO emissions. Both observations confirm the theory.

As expected, roughly 93% of the NO_x emitted in combustion experiments appears as NO; the remaining share is formed as NO_2. The maximum concentration of NO_x is observed when the temperature maxima have been reached for both experiments. This is the case roughly 85 s after the experiments has been started. Another increment

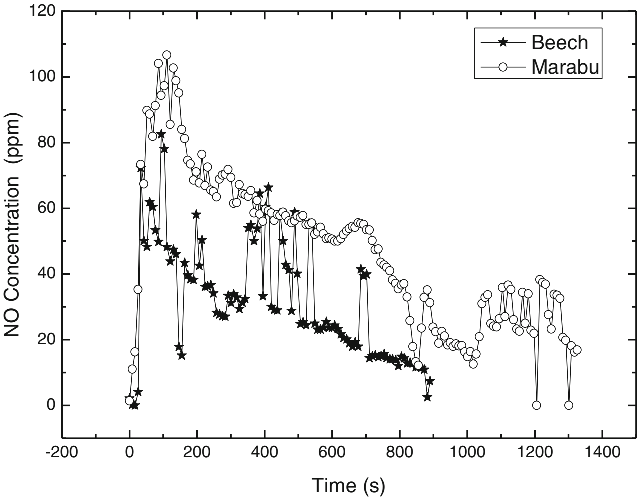

Fig. 5 NO concentration in the exit gas based on the two samples

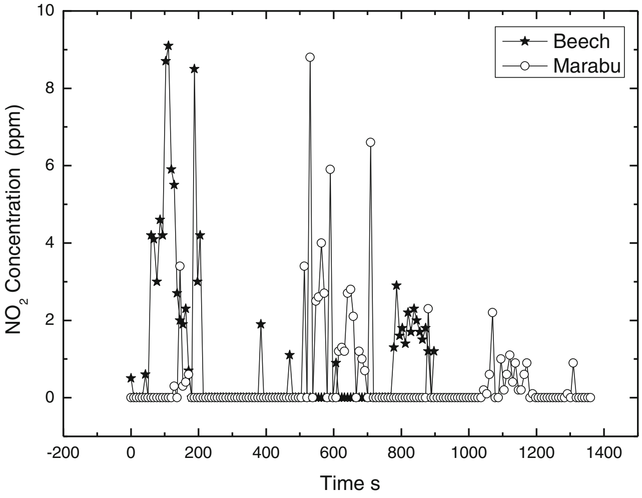

Fig. 6 NO$_2$ concentration in the exit gas based on the two samples

in the concentration of NO$_2$ is detected after approximately 600 s. The reason for this is that at the vicinity of this time a decrease in temperature of the gas is observed and if excess oxygen is present at the measured temperatures, the conversion of NO into NO$_2$ is preferred (reaction (2)) [18].

All over, the maximum concentration obtained for the NO$_x$ emissions during the combustion experiment of the Marabú sample are 145 mg/Nm^3 (referred to 13% of O$_2$ in dry basis within the flue gas). This corresponds to 271.81 mg/Nm^3 (referred to 6% of O$_2$ in dry basis). This value is clearly lower than the legal limit for solid fuel combustion set to 400 mg/Nm^3 by some governments [9, 17]. For this reason, even the high nitrogen content of the Marabú wood related to other wood types (Table 3) do not hinder an increased use of this woody biomass.

5.3 SO$_x$ emissions

The sulphur content in the fuel leave the combustion based on two pathways: integrated within the ash (i.e. as solid matter) and as part of the flue gas (i.e. in a gaseous status) [17]. Only the latter is usually of relevance because sulphur oxides are toxic for organic life and contribute to the acidification of natural ecosystems due the fact that they form acids together with water within the atmosphere.

In general, SO$_x$ emissions from biomass-fuelled devices are increasing with increasing sulphur content within the fuel [21]. Following this rule, higher SO$_x$ emissions are expected to be released during the combustion of Marabú wood compared to beech wood.

Nevertheless, there are wide variations related to this basic rule due to numerous side effects. Additionally, varying fuel characteristics and complex sulphur chemistry makes the estimation of SO$_x$ emissions difficult. A large number of reactions are involved in the release of sulphur oxides from the fuel. Usually, SO$_2$ is the main form to be found in the SO$_x$ emissions. However, a small fraction of the SO$_2$ is oxidised to SO$_3$ at some point according to Eqs. 3 and 4.

$$S + O_2 \leftrightarrow SO_2 \tag{3}$$

$$2\,SO_2 + O_2 \leftrightarrow 2\,SO_3 \tag{4}$$

This is the reason that on behalf of the overall SO$_x$ emissions here, only the SO$_2$ emissions are measured.

The release or retention of sulphur also depends on the amount of Si available in a sample at temperatures above 900–1,000 K [22]. High silicon content favours the release of sulphur as sulphur dioxide, while a sample lean in silicon show only a slight increase of sulphur release with an increase of temperature. Therefore, the silicon content in the ash of the two samples is analysed. This shows, that the silicon content in the ash of the German beech wood (with bark; i.e. 171 mg/kg [23]) is slightly half of the silicon content in the ash of the Marabú wood sample. Following this effect, higher SO$_x$ emissions are expected from the combustion of Marabú wood compared to beech wood.

Figure 7 show the measured SO$_2$ emissions released during the combustion trial of the two wood samples. It becomes very obvious that the SO$_2$ emissions released by the Marabú wood are clearly higher compared to the beech wood. Thus, again the results expected due to the theoretical analysis are confirmed by the measurement. It is likely that a combination of both aspects outlined above is responsible for this behaviour of the SO$_2$ emissions showed in Fig. 7.

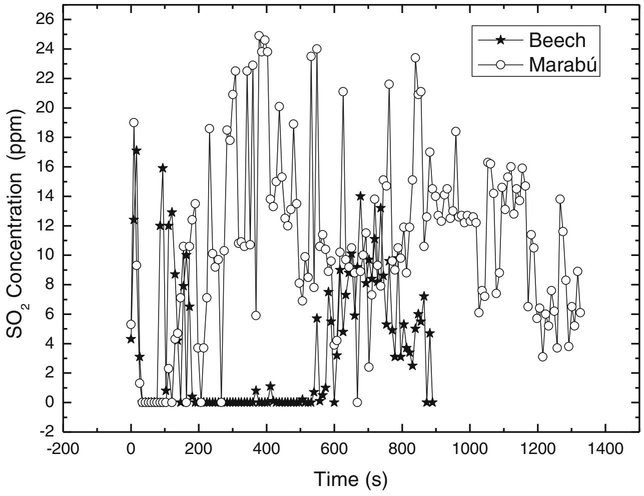

Fig. 7 SO$_2$ concentration in the exit gas based on the two samples

Further investigations [22, 23, 29, 30] showed that part of the released SO_2 is captured by secondary reactions during char burnout and retained in the bottom ash; this process is enhanced by the presence of Ca in the fuel [24, 28]. And Ca is a considerable component within Marabu wood. This could explain the observed behaviour of the SO_2 concentration in the exit gas during the combustions experiments.

The maximum concentration measured for the SO_2 emissions during the combustion of Marabú wood has been 67.95 mg/Nm^3 (with 15.1% O_2 on a dry basis in the flue gas). This corresponds to 169.87 mg/Nm^3 with 6% of O_2 in dry basis. Thus, the combustion of Marabú wood would be possible by meeting the legal emission limits [9, 17] currently at 200 mg/Nm^3 with 6% of O_2 in dry basis in most countries without any secondary flue gas treatment measures.

5.4 Carbon monoxide emissions

During the thermochemical conversion of solid biomass, ideally the carbon is fully converted to carbon dioxide-releasing energy. This conversion of the fuel-C to CO_2 takes place through several intermediate steps resp. different reaction pathways. Carbon monoxide (CO) is the most important intermediate of these conversion processes.

Carbon monoxide is harmful to humans because it hinders the oxygen transport of the blood. This is one of the reasons why there are strict emission limits on CO in most countries. Additionally, high CO emissions are lowering the overall conversion efficiency because CO is oxidised to CO_2 releasing energy.

During the thermochemical conversion of solid biofuels, the fuel-C is converted to carbon dioxide mainly according to Eqs. 5 and 6.

$$C + \frac{1}{2}O_2 \rightarrow CO \tag{5}$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \tag{6}$$

However, due to thermodynamic constraints, a full conversion of the fuel-C to CO_2 is rarely achieved. In practical applications, always a (small) part of the fuel-C is oxidised to the intermediate step, carbon monoxide, only. As a rule of thumb, it can be stated that the lower the CO emissions are the better the combustion device is.

The rate at which CO is oxidised to CO_2 depends among others on the temperature level the reaction takes place, on the quantity and method of supplying the combustion air and on the residence time of the flue gas within the hot part of the combustion chamber. For a given combustion device, usually CO emissions will reach a minimum at a specific air-to-fuel ratio. Higher excess air ratios will result in decreased combustion temperatures, while lower excess air ratios will result in inadequate mixing conditions. Thus, to minimise the CO emissions, the following aspects have to be fulfilled: sufficient residence time, high temperatures and good mixing within the combustion chamber. Thus, high CO emissions are an indicator for insufficient combustion devices and/or a bad operation management. Only to a minor extent, the CO content within the flue gas is defined by the fuel characteristics.

Figure 8 shows the CO emissions measured during the two experiments.

This graphic indicates relatively high values for Beech compared to Marabú. The maximum value for the CO emission in the experiments with beech wood was measured at the same time the maximum value of CO_2 has been released. That means, that there are no optimal conditions for the fully oxidation of the CO to CO_2 within the combustion chamber. The opposite case occurs with the Marabú wood. Here, the maximum value of CO_2 is observed when the minimum value of CO is measured in the flue gas under the same experimental conditions.

The concentration of CO observed in both case suggesting an adjustment of the air–fuel ratio to allow for a full oxidation. Nevertheless, the experimental conditions for both experiments have been the same. But, according to the measured CO emissions, under the selected experimental conditions, they are closer to the ideal conditions for the combustion of Marabú wood due to the slightly different fuel characteristics compared to Beech wood.

The theoretical analysis as well as the measurement results shows that there is no obvious reason related to

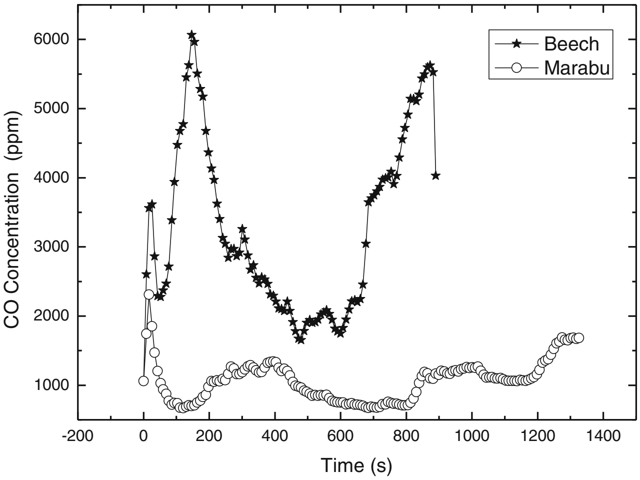

Fig. 8 CO concentration in the exit gas based on the two samples

the CO emissions why Marabú wood should not be used as a renewable source of energy in combustion devices adapted to the specific fuel characteristics of this type of wood.

5.5 Total hydrocarbon emissions

During the thermochemical conversion, solid biomass is heat-induced decomposed (i.e. pyrolytic decomposition). The produced volatiles are usually combusted to CO_2 and H_2O releasing energy. To ensure that these volatiles are fully oxidised, a good mixture with enough combustion air at high temperatures and a sufficient residence time are necessary (i.e. similar conditions as for the conversion of CO to CO_2; “Calorific value” section). Thus, high emissions of hydrocarbons are an indicator for incomplete combustion. Like the CO emissions within the flue gas, the release of hydrocarbons is mainly determined by the design and operation of the combustion device and to lower extends by the fuel characteristic.

The emissions of hydrocarbons are measured as total hydrocarbons (THC) composed of methane, nonmethane hydrocarbons including volatile organic compounds, polycyclic aromatic hydrocarbons and tars. Some of the hydrocarbons summarised under the THC emissions might be toxic to humans and/or the environment. Additionally, they are responsible for the typical wood combustion smell. Beside this, they are lowering the overall conversion efficiency because hydrocarbons can be oxidised to H_2O and CO_2 releasing heat.

Figure 9 show the THC emissions measured in both experiments. According to this, the THC emissions do not show significant differences. They are slightly higher for Beech wood at the first part of the experiment and later the emissions of these components are lower than the emission during Marabú wood combustion. For the latter, the emissions remain more stable through all the combustion process.

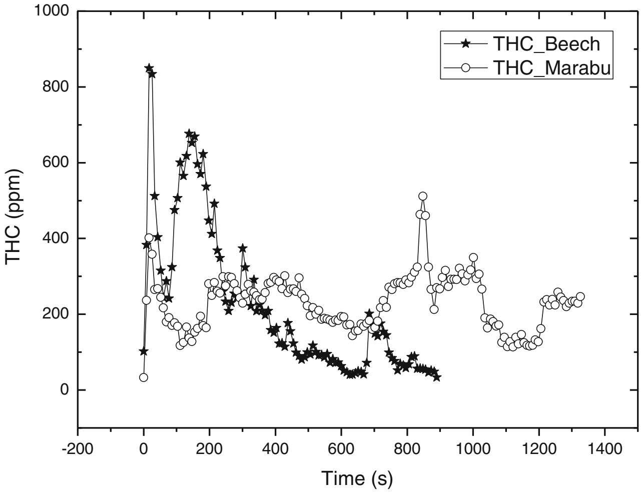

Fig. 9 THC concentration in the exit gas based on the two samples

The fact that these emissions occur is an indicator of non-ideal combustion conditions. Consequently, the experimental layout has not been optimised for the fully combustion of the Marabú as well as the beech wood.

The theory outlined above as well as the measurements shows that related to the THC emissions, Marabú wood could be used as an energy carrier in combustion devices adapted to this type of wood.

6 Final considerations

The goal of this paper is it to analyse the fuel characteristics of *D. cinerea* as a possible crop the provision of solid biofuels. The outlined results can be summarised as follows.

- Compared to other woody and herbaceous biomass, Marabú shows similar fuel properties. In average, the fuel properties are closer to woody biomass than to herbaceous biomass. Referring to these data, there is no reason why wood from Marabú cannot be used as a promising solid biofuel.
- The emissions released during the combustion of Marabú wood are similar or slightly higher compared to the emissions of Beech wood. The higher values of some airborne emissions are due to the higher amount of some trace elements within Marabú compared to Beech wood. Nevertheless, the combustion of Marabú wood is possible with low emissions promising an environmental sound combustion.

Due to these promising findings, there are no obvious reasons hindering a wider use of Marabú as a solid biofuel. This is especially true due the fact that this crop is not native in large area where it can be found today. Additionally, for example in Cuba, this plant is occupying huge land resources needed to grow food and fodder. Thus, the use of Marabú as an energy bioresource could additionally contribute to solve also other challenges. Therefore, energy provision from Marabú can be highly recommended in most cases.

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