









Full assessment of *Sida* (*Sida hermaphrodita*) biomass as a solid fuel

Nicolai D. Jablonowski¹  | Tobias Kollmann² | Martin Meiller³  | Matthias Dohrn^{4,5}  | Michael Müller⁴  | Moritz Nabel^{1,6}  | Petra Zapp⁷  | Andreas Schonhoff⁷  | Silvia D. Schrey¹ 

¹Forschungszentrum Jülich GmbH, Institute of Bio- and Geosciences, IBG-2: Plant Sciences, Jülich, Germany

²Project Management Jülich, PTJ-ESN: Energiesystem: Nutzung, Jülich, Germany

³Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, Institute Branch, Sulzbach-Rosenberg, Germany

⁴Forschungszentrum Jülich GmbH, IEK-2: Microstructure and Properties of Materials, Jülich, Germany

⁵RWE Power Aktiengesellschaft, Forschung und Entwicklung, Kraftwerkstechnik & Speicher, Mineralogie, Bergheim, Germany

⁶German Federal Agency for Nature Conservation – BfN, Bonn, Germany

⁷Forschungszentrum Jülich GmbH, IEK-STE: Institute of Energy and Climate Research, Systems Analysis and Technology Evaluation, Jülich, Germany

Correspondence

Nicolai D. Jablonowski, Institute of Bio- and Geosciences, IBG-2: Plant Sciences, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany.
Email: n.d.jablonowski@fz-juelich.de

[Correction added on 13 July 2020, after first online publication: the affiliations for Matthias Dohrn and Michael Müller have been updated in this current version.]

Abstract

Due to an increased awareness of climate change and limited fossil resources, the demand for alternative energy carriers such as biomass has risen significantly during the past years. This development is supported by the idea of a transition to a bio-based economy reducing fossil-based carbon dioxide emissions. Based on this trend, biomass for energy is expected to be used in the EU mainly for heating until the end of the decade. The perennial herbaceous mallow plant *Sida hermaphrodita* (L.) Rusby ('Sida') has high potential as an alternative biomass plant for energy purposes. Different density cultivation scenarios of *Sida* accounting for 1, 2, or 4 plants per m² resulted in a total biomass yield of 21, 28, and 34 tons dry matter/ha, respectively, over a 3-year period under agricultural conditions while the overall investment costs almost doubled from 2 to 4 plants per m². Subsequently, *Sida* biomass was used as SI) chips, SII) pellets, and SIII) briquettes for combustion studies at pilot plant scale. Pellets outcompeted chips and briquettes by showing low CO emission of 40 mg/Nm³, good burnout, and low slagging behavior, however, with elevated NO_x and SO₂ levels. In contrast, combustion of chips and briquettes displayed high CO emissions of >1,300 mg/Nm³, while SO₂ values were below 100 mg/Nm³. Contents of HCl in the flue gas ranged between 32 and 52 mg/Nm³ for all *Sida* fuels tested. High contents of alkaline earth metals such as CaO resulted in high ash melting points of up to 1,450°C. Life cycle assessment results showed the lowest ecological impact for *Sida* pellets taking all production parameters and environmental categories into consideration, showing further advantages of *Sida* over other alternative biomasses. Overall, the results indicate the improved applicability of pelletized *Sida* biomass as a renewable biogenic energy carrier for combustion.

KEYWORDS

ash, biogenic energy source, combustion, life cycle assessment (LCA), perennial energy crop, slagging, Virginia fanpetals, Virginia mallow

1 | INTRODUCTION

Due to an increased awareness of both climate change and limited fossil resources, the demand for alternative energy carriers such as plant biomass has risen significantly during the past years. The use of biomass for energy generation is a central component of sustainable societies. In particular, in conjunction with fluctuating renewable energy sources like wind and solar power, storable biomass is a key to a stable and secure energy supply (Szarka, Eichhorn, Kittler, Bezama, & Thrän, 2017).

The usage of biomass as an energy carrier is supported by the idea of a transition to a bio-based economy reducing fossil-based carbon dioxide emissions (Langeveld, Dixon, & Jaworski, 2010). Ambitious goals were set for the European Union (EU) in the Renewable Energy Directive targeting of at least 32% for the share of renewable energy consumed in the EU in 2030, making the EU a global leader in renewable energy to cut carbon dioxide emissions (European Parliament and Council, 2018). A revised Renewable Energy Directive took into account specific objectives, aiming for 'developing the decarbonisation potential of advanced biofuels' and 'develop renewable energy potential in the heating and cooling sector' (Council of the European Union, 2017)—to which biogenic solid fuels provide a substantial contribution. Based on the current trend, biomass for energy is expected to be used mainly for heating in the future (Council of the European Union, 2014; WBA, 2018).

The perennial herbaceous mallow plant *Sida hermaphrodita* (L.) Rusby, also known as Virginia fanpetals (hereafter referred to as *Sida*), has been described in the early 1980s (Spooner & Hall, 1983). The awareness for its potential as an alternative biomass plant for energy purposes increased considerably since 2009 (Borkowska & Molas, 2012; Borkowska, Molas, & Kupczyk, 2009; Howaniec & Smoliński, 2011). Among its use as a biogenic energy source and its potential as a feedstock for combustion, biogas, or hydrogen-rich gas production (Howaniec & Smoliński, 2011; Jablonowski et al., 2017), *Sida* was subject of few research activities related to its cultivation (Kurucz, Antal, Gábor, & Popp, 2014; Nabel, Temperton, Poorter, Lücke, & Jablonowski, 2016), and its use for phytoremediation on heavy-metal-contaminated soils (Kocoń & Jurga, 2017; Kocon & Matyka, 2012; Krzywy-Gawrońska, 2012). With regard to its agricultural cultivation, the optimal planting density of *Sida* is crucial in terms of biomass yield and sustainable biomass production (von Gehren et al., 2019). Domestically produced, *Sida* biomass can contribute to national energy security due to its high caloric value and its tolerance for a broad range of soil conditions (Jablonowski et al., 2017). In terms of sustainability and ecosystem services, *Sida* appears to be very promising due to its perennial and flowering nature and its ability to grow on marginal soils (Nabel, Schrey, Poorter, Koller, & Jablonowski, 2017; Nabel et al., 2016). Particularly, the latter

aspect is of importance when it comes to land-use and food-versus-fuel conflicts for biomass production, which could be avoided if the worldwide potential of marginal soils is considered (Cai, Zhang, & Wang, 2011; Krasuska, Cadórniga, Tenorio, Testa, & Scordia, 2010; Zhuang, Jiang, Liu, & Huang, 2011). However, the current scientific data available on *Sida* as an alternative but promising solid fuel are still scarce.

Within this study, we analyzed different *Sida* density cultivation scenarios under agricultural conditions, plant establishment, harvest, and yield of *Sida* biomass over a 4-year period in total, that is, including the year of planting, which was not considered for harvest due to low biomass yields. Subsequently, the *Sida* biomass was investigated as a solid fuel for combustion, applying *Sida* in three different forms of dried biomass, that is, SI: shredded biomass, SII: pellets, and SIII: briquettes, followed by detailed ash analysis, economic calculations, and an overall life cycle assessment (LCA).

A key challenge is the heterogeneity of biomass reflected by the wide range of combustion properties of different biomass feedstocks, such as their chemical composition (Jenkins, Baxter, Miles, & Miles, 1999). Accordingly, it is important to gain basic information and practice-relevant data on the combustion behavior of biogenic feedstocks to expand the usable biomass potential and to develop solutions that enable the cost-effective exploitation of alternative fuels.

The necessity of a stable long-term combustion of a biogenic fuel is mainly affected by the elemental composition of the biomass and its ash. Besides the calorific value, the resulting flue gas composition and the chemical composition of the ash are generally considered to classify the usability of a solid fuel. According to Vassilev et al., biomass is often highly enriched in manganese, potassium, phosphorus, and chlorine (Vassilev, Baxter, Andersen, & Vassileva, 2010) and these elements can cause severe technical problems such as sintering or erosion due to acid formation during the combustion process (Vassilev, Vassileva, Song, Li, & Feng, 2017). Especially potassium as an alkaline can lead to severe slagging in a silicate-rich matrix due to a massive reduction of the eutectic temperature.

In the context of environmental and health protection, the emissions of harmful gases, such as nitrogen oxides (NO_x), carbon monoxide (CO), and unburned hydrocarbons or fine dust must be reduced to a tolerable minimum. Against this background, emissions legislation and regulations get tighter not only at European level (European Parliament and Council, 2008, 2015) but also at national and municipal levels.

To evaluate *Sida* biomass and its usage considering three different dried biomass forms from an ecological perspective, an LCA was conducted. LCA allows the quantification of system-caused environmental impacts using defined impact

categories (ISO14040, 2006). Furthermore, the determination of appropriate boundaries of the systems investigated, combined with available and useful real data, enables ecological sustainability benchmarking with comparable systems.

2 | MATERIALS AND METHODS

2.1 | Experimental cultivation site and set-up

The experimental field for *Sida* cultivation was located in Titz Sevenich, Germany (100 m a.s.l., 50°58'13.0"N 6°23'31.0"E, using ETRS89). The field soil was classified as a clayey silt, composed of 5.6% sand (0.063–2.0 mm), 79.0% silt (0.002–0.063 mm), and 15.4% clay (<0.002 mm; all determined in accordance with VDLUFA Methodenbuch Band I, 2012, C 2.2.1), with pH 7.0 (CaCl₂). The soil contained 41 kg/ha NO₃, <1 kg/ha NH₄, 760 mg/kg P₂O₅, 460 mg/kg K₂O, and 100 mg/kg Mg, and a humus content of approx. 2.3%, all measured in samples from 0 to 30 cm depth. Prior to planting, the field soil was prepared to obtain a fine crumbly seedbed. Root cuttings of *Sida* for propagation were obtained from own plantations (Jablonowski et al., 2017), and were placed approx. 5 cm below ground using a two-rowed semi-automated potato planter in March 2015. Root cuttings were planted in three different densities to evaluate the plant-density-related biomass yield, and the overall plant performance related to stand density: (a) one root cutting per m²; (b) two root cuttings per m²; and (c) four root cuttings per m², planted in four rows each, with a row distance of 0.75 m and a length of 50 m. This resulted in an experimental field totaling approx. 450 m², with approx. 150 m² for each planting density. Subsequently, half of the planting rows were compacted by rolling to evaluate if soil compaction had an effect on germination and shooting. Before *Sida* re-growth, 100 kg/ha of nitrochalk (equalling 27 kg N/ha) was applied in March 2016 to promote *Sida* growth and thus suppress weeds. In April 2016, the herbicide GoltixGold (2 L/ha, 700 g/L Metamitron [59.7 weight-%]) was applied to the *Sida* field at BBCH *Sida* development stage 14 (i.e., four *Sida* leaves present; Jablonowski et al., 2017) to control undesired weed growth. In the following, weed was removed manually. For this investigation, *Sida* biomass was used from three consecutive years (2016, 2017, and 2018), that is, from its second until its fourth year after establishment. Biomass from its establishment year 2015 was not considered for this research due to relatively small quantities.

2.2 | Biomass sampling and preparation

For the evaluation of biomass yield related to planting density, dried *Sida* shoots were collected manually from five

individual square meters for each planting density in February to March in three consecutive years (2016, 2017, and 2018). The number of shoots and maximum shoot height of each individual plant was recorded. All samples were freshly weighed, individually shredded (<2 cm) and homogenized at place using a Viking GB 460C, and subsequently dried at 60°C to determine their dry weights using five subsamples of approx. 500 g. Values were extrapolated to obtain the mean dry matter biomass yield per hectare.

For processing and combustion, the entire biomass from the field was harvested, shredded, and homogenized operating a Claas Jaguar crop chopper before *Sida* re-growth. Residual water content of the entire biomass was determined for recalculation purposes of the biomass as mentioned above, accounting for 19% (±4%) for all three biomass harvests. Biomass was stored and shipped in big-bags for further processing and combustion analysis.

2.3 | Statistical analysis

The field experiment has a one factorial design with the factor planting density separated into three levels: 1, 2, or 4 *Sida* plants per m². Five biological replicates harvested completely randomized in three consecutive years were used for each treatment level. Statistical analysis was performed with analysis of variance in R 3.0.3 (The R Foundation for Statistical Computing 2014) using the work package 'Agricolae' (de Mendiburu, 2014).

2.4 | Biomass processing

For biomass combustion and ash analysis, the *Sida* biomass was either SI) shredded, SII) shredded and pressed into pellets or SIII) shredded and pressed into briquettes. Briquettes were produced employing a Mutek MPP280S briquetting press, with an operational capacity of 150 kg/hr and a power requirement of 8 kWh per 150 kg shredded *Sida* biomass. The obtained *Sida* briquettes were of solid nature, with a cylindrical shape of approx. 60 mm height, and 80 mm in diameter, with a bulk density of approx. 660 kg/m³.

Pilot scale tests were carried out to evaluate the feasibility of pelletizing *Sida*, employing a flat die press (screwpress GmbH, KKP 200). The stated power of the engine amounts to 7.4 kW with a maximum throughput of 150 kg/hr. Since the available *Sida* biomass was limited, the press was preheated with rapeseed cake. The loose *Sida* chips were mixed with water and molasses (BayWa AG) containing 28.13% C, 7.76% H, 1.67% N, and 0.27% S, using a mixing ratio of 98:1.5:0.5.

A batch of approximately 125 kg *Sida* pellets was produced and the power consumption and the throughput of pellets were determined. Subsequently, a sieve analysis was performed to

determine the fine content of the pellets based on DIN EN ISO 17827-1 (ISO 17827-1, 2016). It is noteworthy that in the case of pelletizing, the combustion behavior can be improved by the addition of additives to reduce the slagging tendency of the fuel (Zeng, Pollex, Weller, Lenz, & Nelles, 2018). In the case of pelletizing Sida, no additives were added to increase the ash softening point, as for Sida ash no slagging problems were expected due to its high melting temperature, as reported in an earlier study (Jablonowski et al., 2017).

2.5 | Combustion and emission analysis

Sida chips and pellets were tested operating a grate furnace (HDG Bavaria Compact C 100) with a nominal heat output of 100 kW. The furnace was equipped with a moving step grate, and the removal of the grate ash and fly ash was realized separately via two screws into separate containers.

Sida briquettes were tested in a wood burning stove (Carborobot furnace, C40 Bio Farmer), combining a rotary grate for bulk materials with a combustion chamber for log wood or briquettes, and had a nominal heat output of 40 kW.

All systems were equipped with additional temperature sensors, volume flowmeters, and pressure sensors and were connected to a superordinate programmable logic controller allowing an automated evaluation of the test data.

In all experiments, the system was heated up with wood pellets first. After the heating process, the respective Sida solid fuel was applied. Subsequently, the controllable variables such as mass flow, primary and secondary air, negative pressure in the combustion chamber, and the settings of the grate were adapted to allow an optimized operation.

The Sida test fuel was weighed in batches to determine the mass flow of the different Sida fuels, that is, chips, pellets, and briquettes. A Multi Component Analyzer (MCA 04 of Dr. Födisch AG) was employed to analyze and monitor the composition of the flue gas continuously. For CO, CO₂, NO, NO₂, NH₃, SO₂, HCl, and H₂O, an infrared absorption analyzer, and for O₂ a zirconia sensor was used. In addition, gravimetric dust measurements according to the specifications of VDI 2066 were carried out (VDI, 2006).

Values of other biomasses such as Miscanthus pellets, wood chips, and log wood used for comparison were obtained from own investigations (unpublished data) employing the same furnace, settings, and approaches, or were extracted from literature, as indicated.

2.6 | Chemical and mineralogical analyses of Sida fuels and ashes

To characterize the elemental composition of Sida biomass and its ashes, ultimate analyses were applied. The

determination of inorganic elements was performed with inductively coupled plasma with optical emission spectroscopy (ICP OES) for all Sida fuels, namely chips, pellets, and briquettes and their respective ashes obtained from combustion in an ashing furnace at 550°C in air for 24 hr to ensure complete conversion. Subsequently, the ash mineralogy was investigated with X-ray diffraction (XRD) using a Bruker device D4 Endeavor with CuK α anode (40 kV, 40 mA) and a Bragg–Brentano geometry at 0.026° steps with 1 s per step.

To investigate the melting behavior of the ashes, an ash fusion test was performed as follows. Cylindrical pellets with a diameter of 5 mm were pressed with 1 kN preparation pressure and heated to 1,430°C with a heating rate of 5 K/min. For evaluation and according to Pang et al., the temperature-dependent height was normalized by the initial height (Pang, Hewakandamby, Wu, & Lester, 2013).

2.7 | Life cycle assessment analysis

The ecological evaluation by LCA was performed with the software GaBi 9.2 in line with ISO14040 (ISO14040, 2006) and ISO14044 (ISO14044, 2006). The necessary process data were project-generated quantitative results for the main processes and datasets from ecoinvent 3.5 and GaBi 9.2 for the so-called background data (GaBi LCA Databases, 2020; The ecoinvent Database, 2020). Three different cradle-to-gate process chains for dry Sida biomass pathways were assessed. Intermediate products, and thus technology-determining characteristics of the process chains, are chips in process chain SI, pellets in process chain SII, and briquettes in process chain SIII (Figure 1). Furthermore, a comparison with alternative biomass heat production was done using existing datasets from the ecoinvent database, that is, wood pellets and logs. The functional unit (FU) for the process chains of the production and use of Sida chips, briquettes, pellets, and comparable processes was defined as the production of 100 GJ thermal energy.

Considered process chains were divided into four stages, namely biomass production (cultivation; harvesting), production/processing (manufacturing chips, pellets, or briquettes, incl. internal logistics), storage and shipping (incl. external logistics), and combustion (customer storage; small scale furnace). Included process modules are presented in Figure 1. As a superordinate setting, a total field size of 4 ha was assumed, whereby applied parameters were generated by the use of smaller test sites. The design and dimensioning of single biomass production process modules are related to this area size by a harvesting equivalent (kg/ha or m³/ha). The biomass production stage includes the field preparation, plant protection, and harvesting activities. Calculations of fertilizer-distribution-related emissions (heavy metals, ammonia, etc.) were done as described in Nemecek and

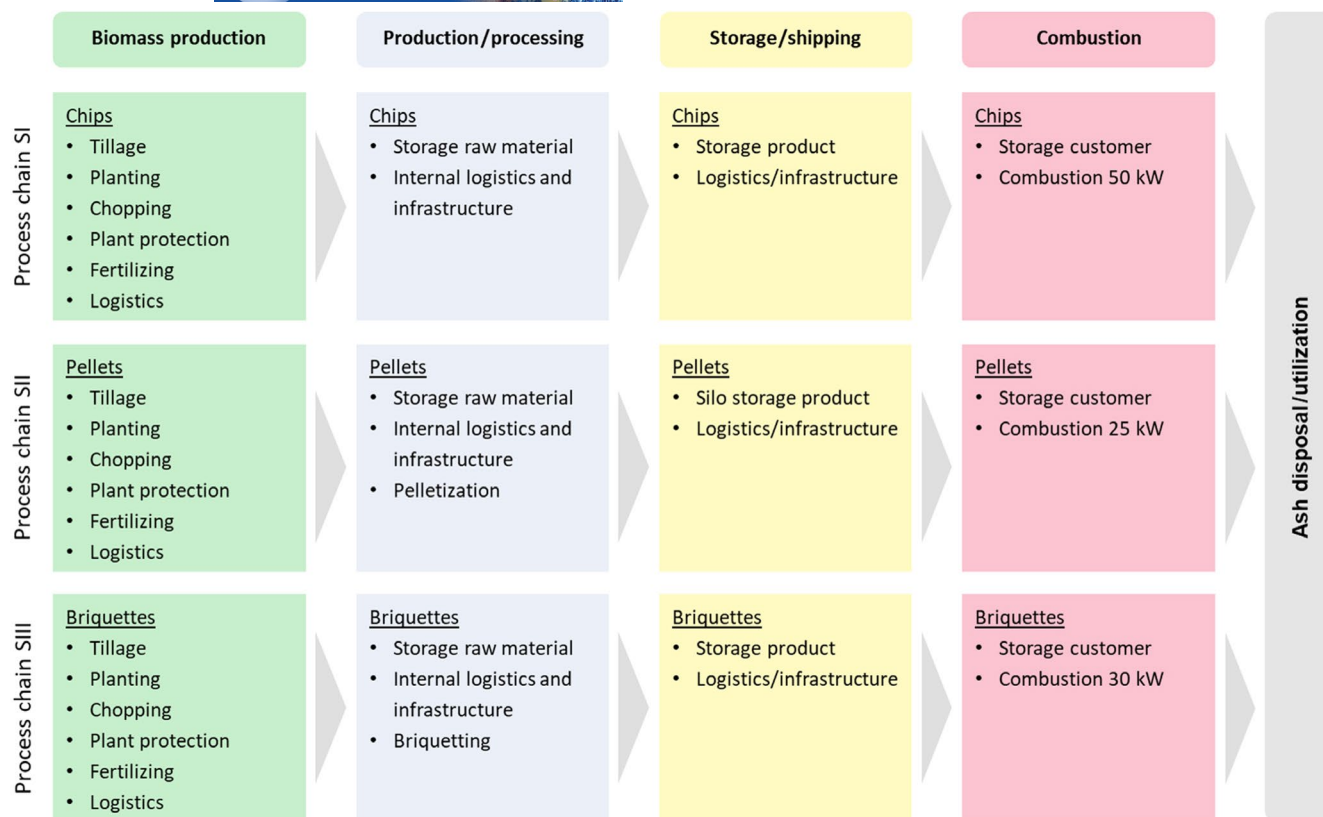


FIGURE 1 Simplified representation of the modeled process chains via the production of Sida chips, pellets, and briquettes (SI, SII, and SIII). SI, process chain chips; SII, process chain pellets; SIII, process chain briquettes

Schnitzer (2011). Production/processing of dry biomass describes logistics, storage of raw material, and the necessary machinery for the transformation of biomass. Machines for pelletizing and briquetting were supposed to be provided by external services. Biomass drying was not taken into account since Sida biomass is harvested in naturally dry state. In the storage and shipping stage internal logistics (e.g., conveyor), product storage and suitable technologies for the delivery to the combustion site were considered. The combustion stage includes product storage on site and the technical facility for combustion, in which the furnaces differ by performance classes. Proportionated impacts from manufacturing machines and buildings were included. Biomass losses along the whole process chain were considered by calculations in line with methods described in Seiffert (2010). To ensure the general consistency of Sida process chains with comparable process chains, the disposal of ash was included as an additional process stage.

The datasets of alternative biomass energy carriers and their combustion are based on Bauer (Bauer, 2007). To run the life cycle inventory analysis for the developed process chains, the newest available data with geographical levels for EU and Germany were used. The impact assessment (LCIA) was performed using 16 midpoint impact categories according to the International Reference Life Cycle Data System, out of which five midpoint categories with the largest impact are shown

exemplarily. By converting absolute results into normalized values in line with the Product Environmental Footprint (PEF; Pilot 1.09, EU-27 (2010)), it is possible to compare different impacts by person equivalents (PE). PE represent the annual environmental impact of an average European citizen (European Commission, 2016; Hauschild & Wenzel, 2001).

It has to be noted that two variables generally worthy of consideration were omitted due to missing data. The first variable is the quantitative effect of Sida growing to soil organic carbon and the consequences for CO₂ sequestration, which depend on factors such as location, soil type, or methods of cultivation. Especially in relation to LCA studies, this topic is discussed in terms of methods (Albers, Avadí, Benoist, Collet, & Hélias, 2019; Qin, Dunn, Kwon, Mueller, & Wander, 2016). According to Bessou et al. (2019), 'there is still no scientific consensus on the best method to assess the holistic impact of land use and land use change within LCA', which additionally illustrates the issues involved, apart from the missing data. As a second omitted topic, the inclusion of a prolonged cultivation comprising multiple cycles has to be mentioned. The distribution over a variety of cycles following the phase considered here is expected to reduce specific environmental burdens. Based on the data used, only a single cultivation and harvesting phase was considered. A further not discussed topic in the present work is the effect of a yield reduction.

3 | RESULTS

3.1 | Plant establishment and biomass productivity

Sida plants grew well leading to a closed canopy after approx. 5 months for all planting densities at BBCH 29 (Jablonowski et al., 2017). Plant development during establishment and in the subsequent year was positively supported by herbicide application, manual weed removal, and the application of nitrochalk. Sprouting of the Sida root cuttings accounted for approx. 80% throughout. Missing plants were replanted to guarantee the planting density in the plots. All root cuttings sprouted equally well irrespective of their size and diameter. No differences in root cuttings germination were observed whether the soil was compacted or not.

In the second year after planting, fungal infections were observed on lower Sida stalks starting in BBCH development stage 51, leading to a bending of long stalks. Such infections were more prominent in the highest planting density, that is, 4 plants/m², but were small overall. Stalk bending was also observed in summer and late autumn due to high wind loads.

Biomass yield increased significantly in the second year after establishment, accounting for 10.3, 12.2, and 17.0 t DM/ha at a planting density of 1, 2, or 4 plants per m², respectively (Figure 2). This reflects a seven- and six-fold biomass increase compared to the first year of harvest in 2016. Except for the planting density of 2 plants per m², the yields decreased moderately in 2018, accounting for 9.6, 13.9, and 14.3 t DM/ha at a planting density of 1, 2, or 4 plants per m², respectively. However, the total produced

biomass over all 3 years was highest for the planting density of 4 plants per m², accounting for 34.3 t DM/ha, followed by 28 and 21.4 t DM/ha for the planting density of 2 and 1 plants per m² (Figure 2).

3.2 | Emissions and combustion characteristics

Wood pellets were used to start the combustion process and heat up the furnace. As soon as the process was stable and the burnout of the gas phase was complete, the three different Sida fuels were injected and emission parameters were evaluated.

3.3 | Sida chips

After switching to Sida chips, CO emissions increased immediately due to the lower energy density of the fuel and the resulting sinking temperatures in the combustion chamber from initially about 845°C to about 420°C. Fuel injection was immediately increased stepwise, resulting again in an increased carbon turnover, indicated by an increase in the CO₂ concentration from about 2%–4%. However, the increase in the fuel input was not enough to raise the temperatures in the combustion chamber sufficiently to achieve a stable and complete combustion. Accordingly, the temperatures in the furnace remained at low level and the reaction conditions in the combustion chamber were insufficient for complete conversion of the carbon in the gas phase resulting in high CO emissions, accounting for 1,347.3 mg/Nm³ (11% O₂ as reference).

3.4 | Sida pellets

Sida pellets were of high quality with a shiny surface. This indicated a high degree of polymerization of the lignin in the fuel, and is considered as an indicator of high stability and low abrasion of the pellets. The mean content of fines accounted for 3.8%. After switching to Sida pellets, the system continued to run with the same parameterization as with wood pellets. The uniform CO₂ concentrations and the uniform temperature profile showed a stable reaction. CO emissions remained at a very low level with 40.2 mg/Nm³. Concentrations of NO_x and SO₂ increased significantly, from 27.2 to 428.6 mg/Nm³ for NO_x, and from 25.9 to 307.2 mg/Nm³ for SO₂ at 11% O₂, respectively. In addition, the loss on ignition of the ash was determined (based on DIN EN ISO 18122), which indicated with a value of 3.41% a good burnout of the solid fuel and low slagging.

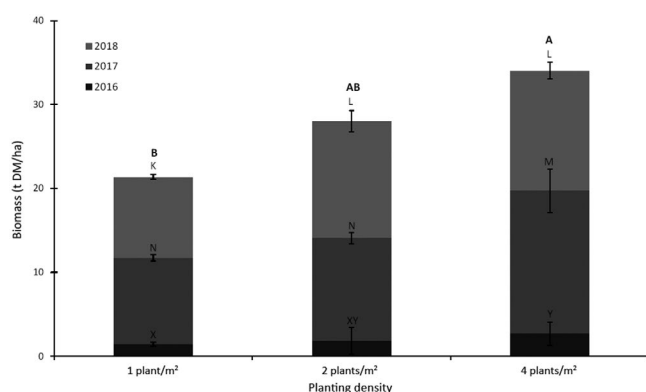


FIGURE 2 Biomass yield in tons dry matter/ha in the first (2016), second (2017), and third (2018) year after Sida establishment calculated on five biological replicates at a planting density of 1, 2, or 4 plants per m². Normal letters indicate the significance between different sowing densities in the individual years of the study. Bold letters indicate the significant differences of the accumulated biomass yield over the years. Values indicated with the same letter are not significantly different ($p > .05$)

3.5 | Sida briquettes

The combustion behavior of Sida briquettes was comparable to the combustion of wood. Overall, the quality of combustion in the stove did not achieve adequate burnout in the gas phase, which in total resulted in very high CO emissions, as presented in Table 1, compared with values of log wood among all average emission values of all tested Sida solid fuels, that is, chips, pellets, and briquettes. To allow a better comparison, Table 1 also represents values from other biogenic solid fuels, that is, Miscanthus pellets, wood pellets, wood chips, and log wood.

3.6 | Slagging behavior

None of the Sida fuel trials encountered slagging problems. Thus, Sida differs significantly from other energy plants, such as Miscanthus, which tend to sinter at temperatures of about 1,126°C (calculated), as shown in Figure 3 obtained from the burning of Sida and Miscanthus pellets. Overall, the ashes from the combustion of Sida pellets were relatively homogeneous and fine-grained (Figure 3, left). While only a few smaller agglomerates (<15 mm) could be found in the combustion of Sida pellets, significant slagging was observed in the same furnace under the same conditions when Miscanthus was burnt (agglomerates with diameters of up to 120 mm, Figure 3, right).

3.7 | Biomass and ash characterization

Results of the elemental and oxide analysis (Table 2) indicated that Sida is a calcium-silicon-rich to calcium-rich biomass with high amounts of alkali metals, especially potassium. In addition, phosphorous compounds were likely to occur due to significant phosphorus content. With reference to the way of processing the biomass, it could be shown that Sida chips and briquettes were chemically equal, but pellets differed in chemical composition. Sida pellets contained higher amounts of potassium, sulfur, and phosphorus.

With reference to Table 2, the variation of calcium and silica within the Sida chips and briquette samples was very high, also affecting the ash content. Therefore, two exemplary compositions are given for chips and briquettes in Table 2, for each one sample with low SiO₂ and high SiO₂ content, respectively. Since SiO₂ is also enriched in the coarse bottom ash of the respective biomass, a contamination with silica sand is likely. All other elements were stable in amount. The high calcium contents led to very high melting points due to the lack of network formers. The coarse fraction of the bottom ash showed high amounts of unburned carbon. The burnout of the briquettes seemed to be better because of lower carbon content in the coarse fraction.

The variation in chemical composition of fuel and laboratory ash samples was not observed for Sida pellets. The variation between raw material, laboratory ash, and bottom

	TSP (mg/Nm ³)	NO _x (mg/Nm ³)	CO (mg/Nm ³)	SO ₂ (mg/Nm ³)	HCl (mg/Nm ³)
Sida pellets	137.0	428.6	40.2	307.2	32.6
Miscanthus pellets	68.88	237.6	65.2	96.3	31
Wood pellets	19.1	27.2	66.8	25.9	28.8
Sida chips	173.42	4	1,347.3	66.8	52
Wood chips	43.6	154.9	130.6	0.3	3.3
Sida briquettes	151.1	38.5	1,980.6	79.9	48.2
Log wood	115	88.8	1,846.6	71.2	39.2

Abbreviation: TSP, total suspended particles.

TABLE 1 Average emission values of all investigated Sida solid fuels, that is, chips, pellets, and briquettes, compared with the biogenic solid fuels Miscanthus pellets, wood chips, and log wood, respectively. All presented values originate from own investigations (unpublished data) conducted at Fraunhofer UMSICHT, Sulzbach-Rosenberg, Germany, employing the same furnace, settings, and approaches

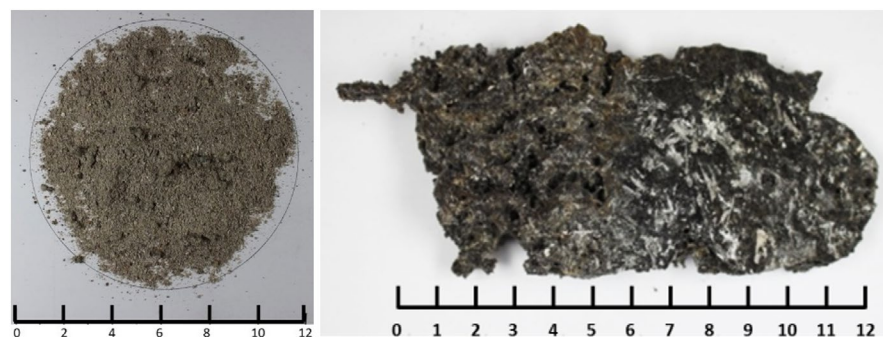


FIGURE 3 Comparison of Sida pellets ashes (left) and a slag agglomerate of Miscanthus pellets, resulting from equal burning conditions

TABLE 2 Elemental analysis and oxide analysis of raw Sida chips, briquettes, and pellets, their 550°C laboratory ashes, and different fractions in the bottom ash of the used boiler for combustion analysis (absolute ash content calculated from ICP OES elements as oxides)

Sample	Absolute wt% in biomass					Normalized wt% in ash									
	Ash	C	S	H	N	Na ₂ O	K ₂ O	CaO	MgO	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	TiO ₂	SO ₃	P ₂ O ₅
Chips #1	2.7	44.6	0.003	6.1	0.3	1.7	11.7	35.0	4.6	1.9	2.4	36.6	0.3	0.2	5.7
Chips #2	2.1	44.0	0.0	6.2	0.2	1.7	12.3	64.6	5.4	0.5	0.4	5.7	1.4	0.0	8.0
Chips 550°C ash #1						1.2	10.0	42.1	4.2	1.7	2.3	30.3	0.3	2.1	5.9
Chips 550°C ash #2						1.1	12.1	62.8	4.8	0.4	0.7	5.5	0.1	2.1	10.4
Chips bottom ash fine						0.9	18.3	43.7	5.0	1.5	1.2	18.6	0.2	0.3	10.2
Chips bottom ash coarse		19.0	0.09	0.8	0.2	0.9	10.2	4.9	1.8	4.5	2.9	70.5	0.6	0.2	3.5
Briquettes #1	2.21	44.4	<0.01	6.0	0.2	2.3	11.5	62.8	7.5	0.6	0.8	6.9	0.1	0.3	7.4
Briquettes #2	4.7	42.5	<0.01	6.1	0.3	0.8	6.0	27.0	2.7	3.4	3.3	52.8	0.3	0.0	3.6
Briquettes 550°C ash #1						1.7	13.8	60.3	5.4	0.3	0.4	5.6	0.0	2.6	10.0
Briquettes 550°C ash #2						0.8	5.1	28.5	2.6	2.0	3.7	52.5	0.4	1.1	3.3
Briquettes bottom ash fine						0.9	8.8	41.2	4.2	2.0	3.1	33.1	0.3	0.4	5.9
Briquettes bottom ash coarse		6.4	0.13	0.3	0.1	0.6	2.4	6.7	1.0	4.1	13.3	70.1	0.9	0.2	0.6
Pellets	2.7	46.3	0.04	6.2	1.2	1.8	21.6	26.9	6.8	3.3	1.3	19.4	0.1	3.8	15.0
Pellets 550°C ash						1.7	20.6	29.2	6.4	3.4	1.2	14.5	0.1	7.2	15.8
Pellets bottom ash fine						1.5	19.0	33.6	6.8	3.7	1.9	15.0	0.2	2.5	15.8
Pellets bottom ash coarse		27.3	0.8	0.6	0.4	1.0	15.8	30.0	7.9	4.1	1.9	17.3	0.2	2.1	19.5

ash was minor, with only small enrichment effects between fine and coarse bottom ash. Nevertheless, Sida pellets also had a high amount of unburned carbon in the coarse fraction.

As the oxide compositions indicated, the mineralogy of all samples also varied widely (Table 3). Calcite,

hydroxylapatite, and periclase were found in all samples in descending amounts. Also, quartz was detected in every sample, although the characterized chips (#2) and pellet ashes indicated higher amounts than the briquette ash (#1). In contrast to the other ashes, pellets contained a high amount of

TABLE 3 Mineral composition of three Sida fuel types 550°C laboratory ashes (o, traces; +, low amount; ++, medium amount; +++, high amount)

550°C ashes	Periclase MgO	Rutile TiO ₂	Quartz SiO ₂	Calcite CaCO ₃	Magnesite MgCO ₃	Fairchildite K ₂ Ca(CO ₃) ₂	Arcanite K ₂ SO ₄	Hydroxylapatite Ca ₅ (PO ₄) ₃ (OH)	Calcium Phosphate			Illite KAl ₂ (Si ₃ Al) O ₁₀ (OH) ₂	Anorthite CaSi ₂ Al ₂ O ₈
									Hydrate Ca ₃ (PO ₄) ₂ •xH ₂ O	Biotite KMg ₂ Al ₂ Si ₃ O ₁₁ (OH)			
Pellets	+	o	+	++	+	o	+++	+++					
Briquettes #1	+		o	+++		+		++	+				
Chips #1	+		++	+++				+	o			+	+

the potassium carbonate (arcanite). Silicates were only found in chips ash.

Furthermore, the Sida ashes were rich in phosphorus while the highest content was found in the coarse bottom ash of Sida pellets with 19.5 wt% P₂O₅ (Table 2). As the XRD results (Table 3) revealed, phosphorus was mainly bound in calcium phosphates.

All ashes from all tested Sida fuels melted at very high temperatures (Figure 4) due to the high amount of alkaline earth elements. Ash from Sida briquettes showed the highest amount of calcium oxide with about 60 wt%. This sample did not even shrink in the investigated temperature range up to 1,450°C.

From the analysis of the fuels, relevant key figures can be derived that are of great relevance for the assessment of the energy use of Sida biomass. Relevant combustion parameters are presented below and compared with values of other fuels either from own analyses or literature data (Table 4). In addition, a comparison was made with requirements from the standard DIN EN ISO 17225-6, which sets quality requirements for fuel pellets made from non-woody biomasses (Table 5).

The following Boie formula (Kaltschmitt, Hartmann, & Hofbauer, 2009) was used to estimate the calorific value (lower heating value [LHV]) from the composition of a fuel (carbon C, hydrogen H, sulphur S, oxygen O):

$$\text{LHV} = 34.8\text{C} + 93.9\text{H} + 10.5\text{S} - 10.8\text{O}.$$

Further empirical formulas were used to estimate the softening and the flow temperature of the ashes, which are in case of Sida in good agreement with the measured ash fusion behavior.

Softening temperature: $\text{DT} = 1,172 - 53.9\text{K} + 252.7\text{Ca} - 788.4\text{Mg}$,

Melting temperature: $\text{FT} = 1,369 - 43.4\text{K} + 192.7\text{Ca} - 698\text{Mg}$.

In Table 4, the results from the elemental analyses and the calculated LHV and melting temperatures of Sida crude biomass (non-processed, i.e., not pelletized or pressed) are compared with other biogenic reference fuels.

Sida is similar to wood in terms of ash softening, and the ash softening temperature higher than that of beech including its bark, poplar, and Miscanthus (Table 4). This shows a significant advantage of Sida over other biogenic energy crops.

The produced Sida pellets were compared in terms of important properties with the requirements for pellets made of non-woody fuels in accordance with DIN EN ISO 17225-6. For the examined parameters, the Sida pellets comply with all the requirements of the standard, with the exception of the content of fines (Table 5).

FIGURE 4 Ash fusion test of the 550°C laboratory ashes of all Sida fuel types. A decrease in the graph indicates a shrinking or melting event

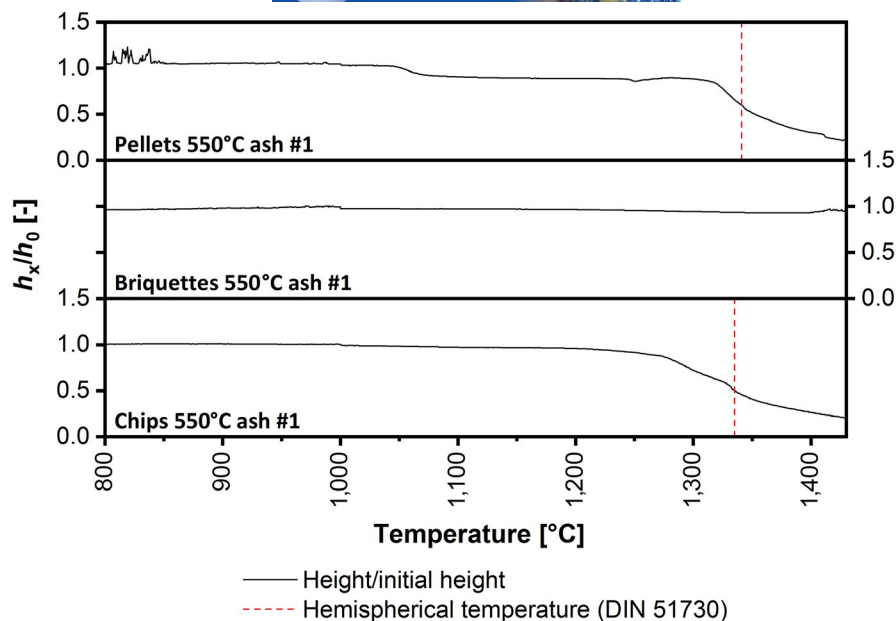


TABLE 4 Biomass composition of Sida and other biogenic fuels or feedstocks and their calculated calorific value using the Boie formula (given values also extracted from Kaltschmitt et al., 2009), and content of the ash-relevant minerals K, Ca, and Mg in Sida ash compared with other relevant biogenic energy feedstocks

Biomass	C (%)	H (%)	O (%)	N (%)	S (%)	LHV (MJ/kg)	K (%)	Ca (%)	Mg (%)	DT (°C)	FT (°C)
Sida (crude)	44.60	6.08	47.38	0.27	0.003 ^a	16.13	0.26	0.67	0.07	1,272.11	1,437.97
Spruce + bark	49.8	6.3	43.2	0.13	0.015	18.59	0.13	0.7	0.08	1,278.81	1,442.41
Beech + bark	47.9	6.2	45.2	0.15	0.015	17.62	0.15	0.29	0.04	1,205.66	1,390.45
Poplar (SRC)	47.5	6.2	44.1	0.35	0.031	17.61	0.35	0.51	0.05	1,242.59	1,417.19
Willow (SRC)	47.5	6.1	44.3	0.26	0.045	17.49	0.26	0.68	0.05	1,290.40	1,453.85
Miscanthus	47.5	6.2	41.7	0.73	0.15	17.91	0.72	0.16	0.06	1,126.32	1,326.70

Abbreviations: DT, softening temperature; FT, melting temperature; LHV, lower heating value.

^aSulfur value range: below detection limits – 0.003.

TABLE 5 Main characteristics of Sida pellets used as a solid fuel are in agreement with the DIN EN ISO 17225-6 requirements

Parameter	DIN EN ISO 17225-6	Sida pellets
Water (w%)	≤12	7.1
Ashes (w%)	≤6	3.59 ^c
Fines (w%)	≤2	3.8
Additives (w%)	≤5	0.5%
LHV (MJ/kg)	≥14.5	16.13 ^a –17.21 ^b
Bulk density (kg/m ³)	≥600	662
Nitrogen (w%)	≤1.5	1.16
Sulfur (w%)	≤0.2	0.04

Abbreviation: LHV, lower heating value, calorific value.

^aValue calculated via Boie formulas.

^bValue experimentally determined, as described in Jablonowski et al. (2017).

^cAshes value range: 2.7–3.6.

3.8 | Energy yield analysis and calorific evaluation of Sida pellets

The energy yield was analyzed based on the experiment with the Sida pellets due to their stable, representative, and reproducible burning behavior. Within our study, no optimal settings could be found for both the Sida briquettes and Sida chips. Sida pellets allowed, however, very stable experimental conditions. Due to this result, we lay our emphasis on the results obtained from the combustion of Sida pellets in the following. During the experiment, 121.5 kg of Sida pellets were fed into the furnace over a period of approx. 3.8 hr, representing a thermal input of 142.12 kW. A cooling water output of 131 kW was measured. Including the sensible heat introduced via air and fuel, this corresponds to a boiler efficiency of 90.85%.

3.9 | Life cycle assessment

Depending on the dry biomass and its processing system, different amounts of *Sida* biomass are necessary for the production of 100 GW heat (FU). The largest input (8,152 kg/FU) can be seen in process chain SI and is mainly caused by low heating values and relatively large losses of biomass. As shown in Table 6 also other input flows differ for each process chain due to varying parameters (e.g., heating value or water content) and the different design and technologies of the process chains. Water, electricity, and energy resources in general are very low for the production of chips because of reduced technology deployment after harvesting. Fertilizer and diesel inputs correlate with the specific field size. Process chain SII contains extra diesel inputs due to truck-driven conveyor technology for blowing the pellets into the storage by compressed air. The biomass loss represents approximately 9%–12% of the primary biomass, whereby the water loss by drying/evaporation is not listed. Resulting ash amounts are <4% of the intermediate product quantities.

As a result of normalization, it is possible to identify the five impact categories with the largest PEs, resource depletion, human toxicity, ecotoxicity, and climate change effects. For these effects, the contribution of the various process stages was assessed. Figure 5 indicates that the largest impacts are caused during the biomass production and the combustion phase in general. In principle, this distribution is also valid for the other 11 categories that are not shown. The

sum of the 16 shown categories indicates that 33%–36% of the PEs are linked to the biomass production stage, while the combustion stage is responsible for 33%–48% of the PEs in the different scenarios (see lower section of Figure 5). Shares between 9% and 16% can be seen for the ash utilization stage. In contrast to these shares, the impact of the further stages is low (<11%).

In the case of the impact category ‘resource depletion, minerals, fossils, and renewables’ (RD mfr), the dominating stage in all process chains can be identified as biomass production and its upstream chains (main reason: P-fertilizer production), whereby the production/processing stage also contributes larger shares (main reason: infrastructure/building). The most clearly expressed share of the ‘human toxicity—cancer effect’ (HT CE) category can be found in the combustion stage (main reason: furnace production). Further relevant impacts of the HT CE category result from the biomass production stage (main reason: fertilizer production). The ‘human toxicity—non-cancer effect’ (HT nCE) category is dominated by the ash utilization and the biomass production (main reason: fertilizer production) while the ‘ecotoxicity freshwater’ (ET Fw) is mainly generated by the ash utilization and combustion stage (main reasons: furnace production). In the ‘climate change’ category (CC), the combustion stage shows the largest impact in all process chains (main reason: combustion). The stage with the lowest impact can be identified as storage and shipping stage in all categories and process chains. Summarizing it can be stated that the process modules with the largest

Flow	Unit	Process chain SI: chips	Process chain SII: pellets	Process chain SIII: briquettes
Inputs				
<i>Sida hermaphrodita</i>	kg/FU	8,152	7,582	7,661
Water	m ³ /FU	6,160	6,131	6,232
Electricity ^a	MJ/FU	1,041	2,396	2,728
Energy resources ^b	MJ/FU	21,642	22,770	23,794
Fertilizer	kg/FU	99.76	92.78	93.75
Diesel	kg/FU	16.52	16.6	15.5
Intermediate products				
<i>Sida</i> chips eq.	kg/FU	6,200	—	—
<i>Sida</i> pellets eq.	kg/FU	—	5,811	—
<i>Sida</i> briquettes eq.	kg/FU	—	—	5,999
Outputs				
Thermal energy	MJ/FU	100,000	100,000	100,000
<i>Sida</i> biomass loss ^c	kg/FU	897.0	644.5	681.0
Ash	kg/FU	127.1	208.6	215.4

TABLE 6 Major input and output flows of the three process chain variants for the production and use of *Sida* chips, pellets, and briquettes

^aDirect electricity demand for the foreground processes.

^bMaterial and energy resources of auxiliary supply chains.

^cDry matter loss.

impacts (PE) can be identified as fertilizer production and use (especially P- and N-fertilizer) during the primary biomass production stage as well as the electricity supply for the manufacturing of the dry biomass. Furthermore, PE increasing process modules can be found as combustion, furnace production, and electricity supply of the combustion stage.

To get a basic impression of the ecological competitiveness, the discussed results of each process chain were compared with other biomass datasets. The aggregated datasets for different biomasses (wood pellets, mixed logs, softwood chips, hardwood chips) show the same magnitude of furnaces' performance classes (25–50 kW) and approximately the same coverage of contained processes. Table 7 shows the

FIGURE 5 Comparison of three process chains by process stages for five selected midpoint impact categories in line with ILCD and summarized values for all 16 ILCD impact categories (B, briquettes; C, chips; CC, climate change; ET Fw, ecotoxicity freshwater; HT CE, human toxicity—cancer effect; HT nCE, human toxicity—non-cancer effect; P, pellets; RD mfr, resource depletion, minerals, fossils, and renewables)

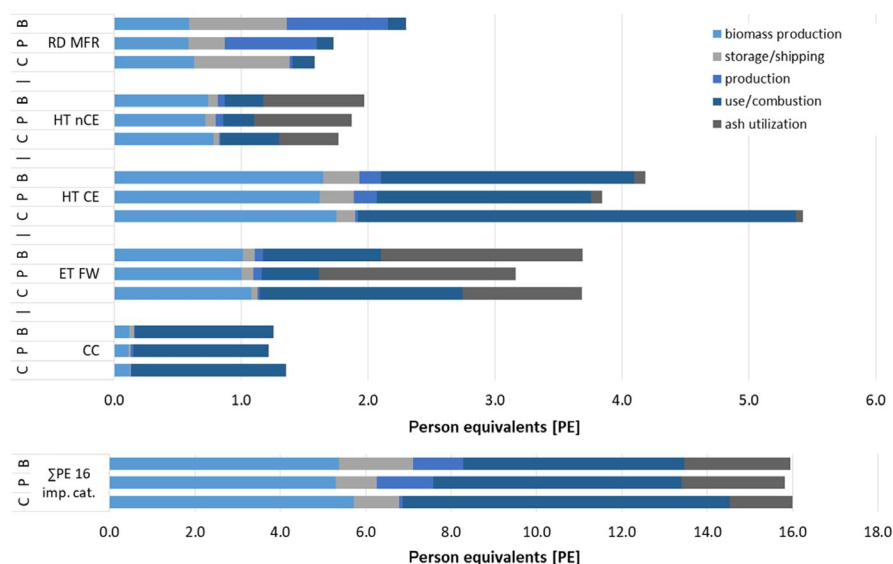


TABLE 7 Comparison of each normalized ILCD impact category for the Sida biomass process chains SI, SII, and SIII with aggregated datasets of alternative biomass energy systems A1–A5

ILCD impact cat.	Equivalent unit	SI	SII	SIII	A1	A2	A3	A4	A5
AC	Mole of H+ eq.	0.27	0.72	0.30	0.37	0.39	0.25	0.60	0.38
CC	kg CO ₂ eq.	1.35	1.22	1.26	1.24	1.32	0.07	1.22	0.25
ET Fw	CTUe	3.68	3.16	3.70	2.45	2.61	1.65	2.48	1.87
EU Fw	kg P eq.	0.48	0.43	0.45	0.64	0.69	0.28	0.60	0.39
EU Ma	kg N eq.	0.10	0.42	0.12	0.36	0.38	0.30	0.67	0.46
EU Te	Mole of N eq.	0.18	0.51	0.20	0.40	0.43	0.34	0.77	0.50
HT CE	CTUh	5.42	3.84	4.18	4.05	4.32	2.20	3.49	2.40
HT nCE	CTUh	1.77	1.87	1.97	5.47	5.83	5.81	7.61	5.57
IR	kBq U235 eq.	0.20	0.21	0.22	0.46	0.49	0.15	0.35	0.08
LU	kg C deficit eq.	0.12	0.10	0.05	0.38	0.40	0.07	0.28	0.58
OD	kg CFC-11 eq.	0.005	0.004	0.005	0.007	0.007	0.003	0.007	0.003
PM	kg PM2.5 eq.	0.29	0.40	0.29	1.50	2.23	1.80	3.16	2.80
PO	kg NMVOC eq.	0.20	0.62	0.27	0.56	0.61	0.98	1.17	0.83
RD w	m ³ eq.	0.36	0.59	0.65	0.25	0.26	0.05	0.27	0.08
RD mfrf	kg Sb eq.	1.57	1.72	2.29	0.62	0.66	0.19	0.62	0.17
Summarized PE		15.99	15.81	15.96	18.75	20.64	14.12	23.28	16.35

Abbreviations: A1, wood pellets, 25 kW, SOTA 2014, CH; A2, wood pellets, 25 kW, CH; A3, mixed logs, 30 kW, CH; A4, wood chips industry, 50 kW, CH, SOTA 2014; A5, hardwood chips, 50 kW, SOTA 2014, RoW; AC, acidification; CC, climate change, incl biogenic carbon; ET Fw, ecotoxicity freshwater; EU Fw, eutrophication freshwater; EU Ma, Eutrophication marine; EU Te, eutrophication terrestrial; HT CE, human toxicity, cancer effects; HT nCE, human toxicity, non-cancer effects; ILCD, International Reference Life Cycle Data System; IR, ionizing radiation, human health; LU, Land use; OD, ozone depletion; PM, particulate matter/respiratory inorganics; PO, photochemical ozone formation, human health; RD mfr, resource depletion, mineral, fossils and renewables; RD w, resource depletion water; SI, process chain chips; SII, process chain pellets; SIII, process chain briquettes; SOTA, state of the art.

exemplary results for the described process chains as well as five alternative biomass systems (Bauer, 2007). While the results in many categories are in a similar value range (e.g., 'acidification freshwater' AC or 'eutrophication freshwater' EU Fw), it can be stated that several impact categories of the Sida biomass-related process chains have lower values than the alternative systems (e.g., 'Particulate matter/Respiratory inorganics' PM) and vice versa (e.g., RD mfr). Considering the values of all impact categories (added up), the lowest amounts are caused by process chain A3 and the Sida biomass cases, which means that these process chains have the lowest overall impact.

4 | DISCUSSION

4.1 | Biomass production

The planting of Sida using root cuttings demonstrates an effective reproduction method under field conditions (Borkowska & Molas, 2013), among seedlings (Nabel et al., 2017; Šiaudinis et al., 2015), since seed germination was found to be very low (10%, e.g., Borkowska & Wardzińska, 2003), but could be increased significantly by appropriate pre-treatments (Von Gehren & Gansberger, 2017). However, the suppression of weeds is crucial to allow a successful plant establishment. Research is needed if herbicide or mechanical treatments could be replaced by soil coverage using compostable plastic films or a layer of biomass, for example, mulch or beneficial intercropping using legumes such as white clover, resulting even in an overall biomass increase and nitrogen enrichment (Nabel, Schrey, Temperton, Harrison, & Jablonowski, 2018). This, in return, can also help to reduce evaporation which can be important in years of low precipitation but also bares the risk to compete with Sida for limited resources (Nabel et al., 2017). The high recorded biomass yields in our present study confirm the major influence of the overall soil quality, precipitation, and local conditions on the Sida plantations compared with other literature data, among fertilization and liming which might be beneficial for plant performance in many cases (Borkowska & Molas, 2013; Borkowska et al., 2009; Šiaudinis, Skuodienė, & Repšienė, 2017). The employed soil compaction after planting of the root cuttings showed no effect on sprouting and plant establishment, underlining the modest nature of Sida as a promising bioenergy crop.

4.2 | Economic evaluation

Market estimates for Sida root cuttings are not available since it is not an established energy crop. While *Miscanthus rhizomes* are sold for approximately 0.16 EUR/piece, Sida root

harvest and preparation is more complicated and the supply and demand is lower, we therefore estimate a price of 0.20 EUR/piece used for our calculations, accounting for 2,000, 4,000, or 8,000 EUR/ha, respectively. Depending on the Sida planting density (1, 2, or 4 plants per m²), we estimated costs for initial field preparation and planting accounting for 375, 450, and 600 EUR, respectively. An adequate planting density of perennial energy crops is crucial during the establishment phase, since further modifications of the planting density are not feasible in an existing vegetation. After successful establishment, more than 20 annual harvests are possible (Borkowska & Molas, 2012). Dividing the high establishment costs by 20 harvests, the financial burden can be significantly reduced. In literature, the energy expenses of Sida growing methods (including planting and annual harvesting) reached 8,630–29,264 MJ/ha (Šiaudinis et al., 2015), while our own calculations account for 10,200 MJ ha⁻¹ year⁻¹, considering the main energy-demanding processes, that is, fertilization and harvest. Annual fertilization and application was estimated using 100 kg N, 100 kg K₂O, and 120 kg P₂O₅/ha (Borkowska et al., 2009), accounting in total for 8,444 MJ/ha, equaling approx. 280 EUR/ha. Annual harvesting costs were calculated with 317 EUR/ha, and a gasoline consumption of 58.9 L/ha, equaling approx. 2,120 MJ/ha.

To date, literature on Sida biomass costs is scarcely available. In Poland, market price estimates for naturally dried Sida chips account for 58.8 EUR/t (Stolarski et al., 2013). Such estimates are difficult for Germany or elsewhere in Europe due to missing Sida production on a comparable level. However, there is a market for *Miscanthus* biomass accounting for 80–100 EUR/t, which can be considered as a price making the cultivation and harvest of such perennial energy crops feasible. However, the applied calculation method can be questioned due to the variable humidity of the biomass, suggesting a payment for the energy contained in the biomass in EUR/GJ.

Employing higher plant densities, that is, 2 or 4 plants versus 1 plant per m², resulted in higher biomass overall. The biomass yield increased by approx. 30% and 60% employing 2 or 4 plants, respectively, compared with 1 plant per m². To obtain the first 30% yield increase (i.e., 2 plants per m²), the investment cost for field establishment almost doubled; however, to gain the next 30% (i.e., 4 plants per m²), the establishment costs increase exponentially, favoring 2 plants per m² overall. Additionally, higher planting densities potentially increase infections with fungi like *Sclerotinia sclerotiorum*, resulting in additional costs for fungicides (Remlein-Starosta, Krzymińska, Kowalska, & Bocianowski, 2016). All mentioned expense factors result in an estimated market net price of 80–100 EUR/t for naturally dried chips of Sida. This price is up to 70% higher compared with earlier data from literature accounting for 58.8 EUR/t (Stolarski et al., 2013), mirroring the different expenses locally for resources and establishment

costs allowing an economically viable cultivation and harvest of *Sida* as a sustainable biomass feedstock for energy generation.

4.3 | Biomass processing and energy yield

Dried *Sida* biomass can easily be harvested using conventional crop choppers as applied for maize. The further treatment of biomass by pelleting offers the chance to change and standardize the physical properties of the *Sida* biomass. Compaction achieves not only a higher bulk density and thus a lower specific transport weight and a higher energy density but also improves the combustion properties by reducing the fine particle content and homogenizing the particle size distribution, simplifying significantly the transport and handling of the fuel. However, the bulk density of *Sida* pellets was lower compared with previous studies (662 kg/m³ vs. 969 kg/m³; Šiaudinis et al., 2015), while still meeting the requirements of the norm DIN EN ISO 17225-6 for pellets made of non-woody biomass. The power consumption needed for the *Sida* pellet production (99.4 kWh/Mg) was in the usual range on pilot plant scale (e.g., 89.2 kWh/Mg wood pellets), but well above the energy requirements of large-scale pelletizing plants, which lie in a range of 40 kWh/Mg pellets, taking only the pressing itself into account (Hartmann, Reisinger, Turowski, & Roßmann, 2013; Hasler & Nussbaumer, 2001). According to DIN EN ISO 17225-6, which is applicable for non-woody biomass fuels, the content of fines (<3.15 mm) is limited to <1%. The norm distinguishes between quality A (fines < 2%) and B (fines < 3%). The determined fines content of 3.8% is due to the production on pilot plant scale. In large-scale plants, an automated recirculation of the fine content takes place via pellet sieving. The increased fine content has to be taken into account when assessing the results from combustion tests. However, all further requirements for pellets made of non-woody fuels were in accordance with DIN EN ISO 17225-6.

4.4 | Combustion and emission characteristics

From all tested *Sida* fuels, pellets showed the best processing and burnout behavior. In contrast, shredded *Sida* (i.e., chips) cannot be used without technological adaptation in the investigated type of furnace, such as adjustment of the conveyor system to allow a constant material flow into the combustion chamber. In addition, it could be observed that finer particles were captured by primary air due to the low specific gravity and transported to the end of the grate. This observation is also evident in the determination of the loss on ignition of the ash obtained from *Sida* chips combustion, which shows

an incomplete solid burnout with 16.91%. Furthermore, the residual moisture content in the *Sida* chips accounting for approx. 19% at harvest may have contributed to the observed initial drop in temperature and higher CO emissions for *Sida* chips. Interestingly, the combustion behavior and emission values of *Sida* briquettes were comparable to log wood, showing that the compaction of *Sida* biomass seems to be advisable for combustion purposes, as well as for transport and storage, compared with the loose *Sida* chips. As shown, our calculated and measured LHV of *Sida* was in accordance with the mean value reported in literature (Nahm & Morhart, 2018), and was comparable to other biogenic sources as indicated in this study. The elemental composition of the evaluated solid *Sida* fuels was in accordance with literature data as well (Stolarski et al., 2014).

Since *Sida* pellets demonstrated best combustion behavior overall, it is noteworthy that the number of firing systems for pellets increased linearly during the last 9 years in Germany, accounting for almost half a million installations in 2019 (FNR, 2019). While private households are by 22.2% the second largest user group of solid fuels from woody resources (FNR, 2019), *Sida* pellets may substitute and contribute to the supply of such biogenic fuels for heat and energy generation.

Even though the content of sulfur as a highly eroding element was low in *Sida* biomass itself, meeting the DIN EN ISO 17225-6 requirements, the SO₂ emissions were relatively high for all solid *Sida* fuels compared with *Miscanthus* pellets, wood pellets or chips, except for log wood. Interestingly, our results on SO₂ were the exception, and cannot be explained with the S content in the biomass or the added molasses for the pellet production. Though unlikely, residual rapeseed cake in the pellets production chain may have contributed to the observed high SO₂ and NO_x emissions. Our values for NO_x and CO in the exhaust gases were significantly smaller when compared to literature data on the combustion of *Sida* pellets (Zajac, Szyszlak-Barglowicz, Slowik, Wasilewski, & Kuranc, 2017). However, the high values given in the reference were explained by technical problems and incomplete pellet combustion. High fluctuation in magnitude of NO, NO_x, and CO depends on fuel feeding methods, the natural N content of the biomass, the combustion temperature, and oxygen flow (Juszczak, 2014). High CO values determined for *Sida* briquettes may be related to the solid, cylindrical nature of the tested briquettes, which likely resulted in incomplete burnout and therefore higher CO evolution.

4.5 | Ash analysis

A lower ash content in biomass used for combustion purposes implicates a higher energy density, and is desirable to avoid high dust loads and therefore pollution and waste. The ash content for all *Sida* solid fuels was lower as or equal to values

reported in other studies on Sida as a solid fuel (2.1%–4.7% vs. 6% or 2.8%, respectively; Šiaudinis et al., 2015; Stolarski et al., 2013), and generally in the lower range when compared to a vast number of biogenic fuels (Vassilev et al., 2017). Sida ash values might be related to a generally high uncertainty factor in the analytical methodology and inhomogeneity of the Sida biomass composition from different locations. However, an ash content of approx. 3% for all tested Sida fuels, and particularly for the pellets meets the DIN EN ISO 17225-6 requirements accounting for a value of <6%. As reported in our earlier study (Jablonowski et al., 2017), we here report high ash melting temperatures which are in line with a previous investigation on Sida used as a solid fuel (von Gehren et al., 2019). The high melting temperatures were due to the lack of network formers like silica or alumina species. Generally, those ashes are not critical for slagging, even though those high alkaline contents can lead to severe sintering. Concerning the network theory (Vorres, 1987), an even combination of alkaline (earth) metals and aluminosilicates including iron and phosphorus should be avoided because of low sintering temperatures and subsequent sintering or slagging on the combustion chamber walls and superheater, or reheater surfaces, respectively, which can increase corrosion and causes reduced heat transfer and thus lower efficiency of the furnace.

The high amount of silicates found in the chips ashes might be due to missing pre-processing in comparison to the other ashes preserving more clays from the Sida experimental field.

The Sida ashes were rich in phosphorus (P), which is an important element if the ash shall be recycled as fertilizer. As shown, phosphorus was mainly bound in calcium phosphates which are only little soluble in water and therefore relatively immobile. Therefore, the ash could likely act as long-term fertilizer, which is a promising option presented in a previous study on other biogenic ashes with similar P contents (Schiemenz & Eichler-Löbermann, 2010). However, it needs further investigation if such high P contents in Sida ashes are generally found elsewhere and if the P-forms are plant available.

Irrespective of the vast variation in the elemental composition of all investigated Sida fuel ashes, the ash melting point and most detected elements were in a similar range as reported elsewhere (Kowalczyk-Jusko, 2009). The high variation in ash composition has to be linked to the different Sida fuels tested in our study, irrespective the fact that the analytical methods display a variation itself even though sample preparation was conducted accurately.

4.6 | Life cycle assessment

The presented results show advantages and disadvantages of the three process chains considered. It can be stated that on

the one hand process chain SII (pellets) needs the lowest biomass input and process chain SIII (briquettes) also tends into this direction in comparison with process chain SI (chips). On the other hand, the specific water, direct electricity, and energy resources consumption are significantly higher in these process chains. Adding the output category 'Sida biomass loss' and 'ash', SI and SII are on a par. Overall, the results show the general effects of an advanced processing after shredding.

By separating each process chain into process stages, possible savings of input flows that have the largest effects can identify starting points for optimization. Involved parties (grower, biomass processors, or heat producer) are able to identify possibilities to influence the ecological impacts. Biomass production and combustion have been identified to be mainly responsible for most impacts, and are therefore suitable intervention points for further analysis.

The comparison of LCIA results among Sida biomass process chains themselves can play a big role in identifying the most ecologically favorable product. The present results show the lowest ecological impact for Sida pellets, closely followed by Sida briquettes and chips. A definite ranking would need a clearer differentiation within the results. The comparison with alternative technologies generates arguments for the competitiveness of Sida biomass. Causes for environmental impacts must be divided into influenceable and non-influenceable for the producer. While fertilizer production itself is not modifiable for consumers, the using conditions (e.g., mass, source, etc.) are. The reduction of fertilizers, the use of biogenic residues, and the choice of location are starting points for optimization of ecological effects, as shown in two earlier studies on the establishment of Sida under marginal soil conditions (Nabel, Schrey, Poorter, et al., 2018; Nabel, Schrey, Temperton, et al., 2018). The furnace production takes place outside the area of influence for the heat producers. To get better values for the combustion process, the optimization of the energy carrier's combustion behavior is an option. Nevertheless, it was illustrated that the use of Sida biomass led to significantly lower PE values than the most alternative biomass routes with wood chips or logs, etc. (four of five cases, Table 7). In the clearest case, an advantage of nearly 50% of the absolute PE value was determined for Sida biomass. Furthermore, a comparison with suitable datasets on fossil energy generation as well as other alternative biomasses (e.g., *Miscanthus*) should be realized. In the present study, this was not possible due to excessive deviations of performance classes (furnace) and other non-compliant conditions. The indicated advantageousness of Sida biomass can be underpinned by further research on >15 different datasets (unpublished data), where >70% of considered alternative process chains turn out to have a larger impact than Sida. Further studies should include the currently much debated topics of soil organic carbon and CO₂ sequestration and,

where appropriate, be based on new corresponding studies. From today's point of view, the ecological impact of *Sida* biomass as an energy carrier makes it a useful alternative to the most compared established solid fuels.

ACKNOWLEDGEMENTS

All presented research was realized via institutional funding of the collaborating institutions. We highly appreciated the constructive comments and suggestions of the anonymous reviewers which helped us to improve our manuscript.

ORCID

Nicolai D. Jablonowski  <https://orcid.org/0000-0002-5298-5521>

Martin Meiller  <https://orcid.org/0000-0002-7225-1322>

Matthias Dohrn  <https://orcid.org/0000-0003-0082-4395>

Michael Müller  <https://orcid.org/0000-0002-2260-0934>

Moritz Nabel  <https://orcid.org/0000-0001-9772-7780>

Petra Zapp  <https://orcid.org/0000-0002-8964-2450>

Andreas Schonhoff  <https://orcid.org/0000-0002-8937-6957>

Silvia D. Schrey  <https://orcid.org/0000-0001-5821-1968>

REFERENCES

- Albers, A., Avadi, A., Benoist, A., Collet, P., & Hélias, A. (2019). Modelling dynamic soil organic carbon flows of annual and perennial energy crops to inform energy-transport policy scenarios in France. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2019.135278>
- Bauer, C. (2007). Teil IX: Holzenergie. In *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Ecoinvent report no. 6-IX*. Retrieved from <http://www.ecoinvent.org>
- Bessou, C., Tailleur, A., Godard, C., Gac, A., de la Cour, J. L., Boissy, J., ... Benoist, A. (2019). Accounting for soil organic carbon role in land use contribution to climate change in agricultural LCA: Which methods? Which impacts? *International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-019-01713-8>
- Borkowska, H., & Molas, R. (2012). Two extremely different crops, *Salix* and *Sida*, as sources of renewable bioenergy. *Biomass and Bioenergy*, 36, 234–240. <https://doi.org/10.1016/j.biombioe.2011.10.025>
- Borkowska, H., & Molas, R. (2013). Yield comparison of four lignocellulosic perennial energy crop species. *Biomass and Bioenergy*, 51, 145–153. <https://doi.org/10.1016/j.biombioe.2013.01.017>
- Borkowska, H., Molas, R., & Kupczyk, A. (2009). Virginia fanpetals (*Sida hermaphrodita* Rusby) cultivated on light soil; height of yield and biomass productivity. *Polish Journal of Environmental Studies*, 18(4), 563–568.
- Borkowska, H., & Wardzińska, K. (2003). Some effects of *Sida hermaphrodita* R. cultivation on sewage sludge. *Polish Journal of Environmental Studies*, 12(1), 119–122.
- Cai, X., Zhang, X., & Wang, D. (2011). Land availability analysis for biofuel production. *Environmental Science and Technology*, 45(January), 334–339. <https://doi.org/10.1021/es103338e>
- Council of the European Union. (2014). *COMMISSION STAFF WORKING DOCUMENT State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU, (SWD(2014) 259 final)*. Retrieved from https://ec.europa.eu/energy/sites/ener/files/2014_biomass_state_of_play_.pdf
- Council of the European Union. (2017). *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the promotion of the use of energy from renewable sources (recast)*. Retrieved from http://eur-lex.europa.eu/resource.html?uri=cellar:3eb9ae57-faa6-11e6-8a35-01aa75ed71a1.0007.02/DOC_1&format=PDF
- de Mendiburu, F. (2014). agricolae: Statistical procedures for agricultural research. R package version 1.2-0.
- ISO 17827-1 (2016). Solid biofuels – Determination of particle size distribution for uncompressed fuels – Part 1: Oscillating screen method using sieves with apertures of 3,15 mm and above (ISO 17827-1:2016). German version EN ISO 17827-1:2016.
- European Commission. (2016). *Guidance for the implementation of the EU product environmental footprint (PEF) during the environmental footprint (EF) pilot phase* (Vol. 5.2(February), pp. 1–95). Retrieved from https://ec.europa.eu/environment/eussd/smgp/pdf/Guidance_products.pdf
- European Parliament and Council. (2008). Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. *Official Journal of the European Union, L152*, 1–44.
- European Parliament and Council. (2015). DIRECTIVE (EU) 2015/2193 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL – Of 25 November 2015 – On the limitation of emissions of certain pollutants into the air from medium combustion plants. *Official Journal of the European Union, L313*, 1–19. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015L2193&qid=1524555867189&from=EN>
- European Parliament and Council. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union, 5(L 328/82)*, 82–209.
- FNR. (2019). *Basisdaten bioenergie Deutschland 2019*. Gülzow-Prützen, Fachagentur Nachwachsende Rohstoffe e. V. (FNR). Retrieved from <https://mediathek.fnr.de/basisdaten-bioenergie.html>
- GaBi LCA Databases. (2020). *GaBi*. Retrieved from <http://www.gabi-software.com/international/databases/>
- Hartmann, H., Reisinger, K., Turowski, P., & Roßmann, P. (2013). *Handbuch Bioenergie Kleinanlagen*. FNR. Retrieved from https://mediathek.fnr.de/media/downloadable/files/samples/h/a/handbuchkleinanlagen2013-web_1.pdf
- Hasler, P., & Nussbaumer, T. (2001). *Herstellung von Holzpellets – Einfluss von Presshilfsmitteln auf Produktion, Lagerung, Verbrennung sowie Energie- und Ökobilanz von Holzpellets: Qualität*. Retrieved from <http://www.verenum.ch/Publikationen/Holzpellets.pdf>
- Hauschild, M. Z., & Wenzel, H. (2001). The European person equivalent: Measuring the personal environmental space. Annual report NATO/CCMS Pilot Study, Clean Products and Processes (Phase I). Report no. 242. U.S. En. Cincinnati, OH. Retrieved from <https://orbit.dtu.dk/en/publications/the-european-person-equivalent-measuring-the-personal-environment>
- Howaniec, N., & Smoliński, A. (2011). Steam gasification of energy crops of high cultivation potential in Poland to hydrogen-rich gas. *International Journal of Hydrogen Energy*, 36(3), 2038–2043. <https://doi.org/10.1016/j.ijhydene.2010.11.049>

- ISO14040. (2006). International Standard ISO 14040: 2006(E) – Environmental management – Life cycle assessment – Principles and framework.
- ISO14044. (2006). Environmental management – Life cycle assessment – Requirements and guidelines.
- Jablonowski, N. D., Kollmann, T., Nabel, M., Damm, T., Klose, H., Müller, M., ... Schurr, U. (2017). Valorization of *Sida (Sida hermaphrodita)* biomass for multiple energy purposes. *GCB Bioenergy*, 9(1). <https://doi.org/10.1111/gcbb.12346>
- Jenkins, B. M., Baxter, L. L., Miles Jr., T. R., & Miles, T. R. (1999). Combustion properties of biomass. *Fuel Processing Technology*, 54, 17–46. [https://doi.org/10.1016/S0378-3820\(97\)00059-3](https://doi.org/10.1016/S0378-3820(97)00059-3)
- Juszczak, M. (2014). Concentrations of carbon monoxide and nitrogen oxides from a 25 KW boiler supplied periodically and continuously with wooden pellets. *Chemical and Process Engineering*, 35(2), 163–172. <https://doi.org/10.2478/cpe-2014-0012>
- Kaltschmitt, M., Hartmann, H., & Hofbauer, H. (Eds.). (2009). *Energie aus Biomasse Grundlagen, Techniken und Verfahren* (2nd ed.). Berlin and Heidelberg, Germany: Springer. <https://doi.org/10.1007/978-3-540-85095-3>
- Kocoń, A., & Jurga, B. (2017). The evaluation of growth and phytoextraction potential of *Miscanthus × giganteus* and *Sida hermaphrodita* on soil contaminated simultaneously with Cd, Cu, Ni, Pb, and Zn. *Environmental Science and Pollution Research*, 24(5), 4990–5000. <https://doi.org/10.1007/s11356-016-8241-5>
- Kocon, A., & Matyka, M. (2012). Phytoextractive potential of *Miscanthus giganteus* and *Sida hermaphrodita* growing under moderate pollution of soil with Zn and Pb. *Journal of Food, Agriculture & Environment*, 10(2), 1253–1256.
- Kowalczyk-Jusko, A. (2009). Ash from different energy crops – Popiół Z Różnych Roslin Energetycznych. *Proceedings of ECOpole*, 3, 159–164.
- Krasuska, E., Cadórniga, C., Tenorio, J. L., Testa, G., & Scordia, D. (2010). Potential land availability for energy crops production in Europe. *Biofuels, Bioproducts and Biorefining*, 4(6), 658–673. <https://doi.org/10.1002/bbb.259>
- Krzywy-Gawrońska, E. (2012). The effect of industrial wastes and municipal sewage sludge compost on the quality of Virginia fanpetals (*Sida hermaphrodita* Rusby) biomass Part 2. Heavy metals content, their uptake dynamics and bioaccumulation. *Polish Journal of Chemical Technology*, 14(3), 8–14. <https://doi.org/10.2478/v10026-012-0078-1>
- Kurucz, E., Antal, G., Gábor, F. M., & Popp, J. (2014). Cost-effective mass propagation of Virginia fanpetals (*Sida hermaphrodita* (L.) Rusby) from seeds. *Engineering and Management Journal*, 13(11), 2845–2852. <https://doi.org/10.30638/eemj.2014.319>
- Langeveld, J. W. A., Dixon, J., & Jaworski, J. F. (2010). Development perspectives of the biobased economy: A review. *Crop Science*, 50(April), S-142–S-151. <https://doi.org/10.2135/cropsci2009.09.0529>
- Nabel, M., Schrey, S. D., Poorter, H., Koller, R., & Jablonowski, N. D. (2017). Effects of digestate fertilization on *Sida hermaphrodita*: Boosting biomass yields on marginal soils by increasing soil fertility. *Biomass and Bioenergy*, 107(October), 207–213. <https://doi.org/10.1016/j.biombioe.2017.10.009>
- Nabel, M., Schrey, S. D., Poorter, H., Koller, R., Nagel, K. A., Temperton, V. M., ... Jablonowski, N. D. (2018). Coming late for dinner: Localized digestate depot fertilization for extensive cultivation of marginal soil with *Sida hermaphrodita*. *Frontiers in Plant Science*, 9. <https://doi.org/10.3389/fpls.2018.01095>
- Nabel, M., Schrey, S. D., Temperton, V. M., Harrison, L., & Jablonowski, N. D. (2018). Legume intercropping with the bioenergy crop *Sida hermaphrodita* on marginal soil. *Frontiers in Plant Science*, 9. <https://doi.org/10.3389/fpls.2018.00905>
- Nabel, M., Temperton, V. M., Poorter, H., Lücke, A., & Jablonowski, N. D. (2016). Energizing marginal soils – The establishment of the energy crop *Sida hermaphrodita* as dependent on digestate fertilization, NPK, and legume intercropping. *Biomass and Bioenergy*, 87, 9–16. <https://doi.org/10.1016/j.biombioe.2016.02.010>
- Nahm, M., & Morhart, C. (2018). Virginia mallow (*Sida hermaphrodita* (L.) Rusby) as perennial multipurpose crop: Biomass yields, energetic valorization, utilization potentials, and management perspectives. *GCB Bioenergy*, 10(6), 393–404. <https://doi.org/10.1111/gcbb.12501>
- Nemecek, T., & Schnetzer, J. (2011). Methods of assessment of direct field emissions for LCIs of agricultural production systems. Data v3.0 (2012). Agroscope Reckenholz-Tänikon Research Station ART, Zurich. Retrieved from https://scholar.google.com/scholar?cluster=2392782133849461686&hl=de&as_sdt=0,5
- Pang, C. H., Hewakandamby, B., Wu, T., & Lester, E. (2013). An automated ash fusion test for characterisation of the behaviour of ashes from biomass and coal at elevated temperatures. *Fuel*, 103, 454–466. <https://doi.org/10.1016/j.fuel.2012.06.120>
- Qin, Z., Dunn, J. B., Kwon, H., Mueller, S., & Wander, M. M. (2016). Soil carbon sequestration and land use change associated with bio-fuel production: Empirical evidence. *GCB Bioenergy*, 8(1), 66–80. <https://doi.org/10.1111/gcbb.12237>
- Remlein-Starosta, D., Krzyminińska, J., Kowalska, J., & Bocianowski, J. (2016). Evaluation of yeast-like fungi to protect Virginia mallow (*Sida hermaphrodita*) against *Sclerotinia sclerotiorum*. *Canadian Journal of Plant Science*, 96(2), 243–251. <https://doi.org/10.1139/cjps-2015-0230>
- Schiemenz, K., & Eichler-Löbermann, B. (2010). Biomass ashes and their phosphorus fertilizing effect on different crops. *Nutrient Cycling in Agroecosystems*, 87(3), 471–482. <https://doi.org/10.1007/s10705-010-9353-9>
- Seiffert, M. (2010). DBFZ Report Nr. 2: Methodische Vorgehensweise zur Standortidentifikation und Planung der Biomassebereitstellung für Konversionsanlagen am Beispiel von Bio-SNG-Produktionsanlagen: DBFZ. Retrieved from <http://webdoc.sub.gwdg.de/ebook/serien/yo/DBFZ/02.pdf>
- Šiaudinis, G., Jasinskas, A., Šarauskis, E., Steponavičius, D., Karčauskienė, D., & Liaudanskienė, I. (2015). The assessment of Virginia mallow (*Sida hermaphrodita* Rusby) and cup plant (*Silphium perfoliatum* L.) productivity, physico-mechanical properties and energy expenses. *Energy*, 93, 606–612. <https://doi.org/10.1016/j.energy.2015.09.065>
- Šiaudinis, G., Skuodienė, R., & Repšienė, R. (2017). The investigation of three potential energy crops: Common mugwort, cup plant and Virginia mallow on Western Lithuania's Albeluvisol. *Applied Ecology and Environmental Research*, 15(3), 611–620. https://doi.org/10.15666/aeer/1503_611620
- Spooner, D. M., & Hall, G. F. (1983). *Sida hermaphrodita* (Malvaceae): Virginia Mallow, a common rarity. *Ohio Journal of Science*, 83(2), 8.
- Stolarski, M. J., Krzyzaniak, M., Śnieg, M., Słomińska, E., Piórkowski, M., & Filipkowski, R. (2014). Thermophysical and chemical properties of perennial energy crops depending on harvest period. *International Agrophysics*, 28(2), 201–211. <https://doi.org/10.2478/intag-2014-0009>
- Stolarski, M. J., Szczukowski, S., Tworowski, J., Krzyzaniak, M., Gulczyński, P., & Mleczek, M. (2013). Comparison of quality and production cost of briquettes made from agricultural and

- forest origin biomass. *Renewable Energy*, 57, 20–26. <https://doi.org/10.1016/j.renene.2013.01.005>
- Szarka, N., Eichhorn, M., Kittler, R., Bezama, A., & Thrän, D. (2017). Interpreting long-term energy scenarios and the role of bioenergy in Germany. *Renewable and Sustainable Energy Reviews*, 68, 1222–1233. <https://doi.org/10.1016/j.rser.2016.02.016>
- The ecoinvent Database. (2020). *Ecoinvent*. Retrieved from <https://www.ecoinvent.org/database/database.html>
- Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2010). An overview of the chemical composition of biomass. *Fuel*, 89(5), 913–933. <https://doi.org/10.1016/j.fuel.2009.10.022>
- Vassilev, S. V., Vassileva, C. G., Song, Y. C., Li, W. Y., & Feng, J. (2017). Ash contents and ash-forming elements of biomass and their significance for solid biofuel combustion. *Fuel*, 208, 377–409. <https://doi.org/10.1016/j.fuel.2017.07.036>
- VDI. (2006). VDI/DIN-Handbuch Reinhaltung der Luft, Band 4: Analysen- und Messverfahren. VDI 2066: Messen von Partikeln, Staubmessung in strömenden Gasen, Gravimetrische Bestimmung der Staubbeladung – Particulate matter measurement, Dust measurement in flowing gases, Gravimetric determination of dust load.
- Von Gehren, P., & Gansberger, M. (2017). Investigating the type of dormancy, imbibition and germination of *Sida hermaphrodita* seeds and its practical application in a sowing experiment. *Seed Science and Technology*, 45(2), 269–281. <https://doi.org/10.15258/sst.2017.45.2.14>
- von Gehren, P., Gansberger, M., Pichler, W., Weigl, M., Feldmeier, S., Wopienka, E., & Bochmann, G. (2019). A practical field trial to assess the potential of *Sida hermaphrodita* as a versatile, perennial bioenergy crop for Central Europe. *Biomass and Bioenergy*, 122(January 2019), 99–108. <https://doi.org/10.1016/j.biombioe.2019.01.004>
- Vorres, K. S. (1987). The relationship between cation mobility and acid-base behavior in coal ash and similar oxide systems. Abstracts of Papers of the American Chemical Society. In *Fuel* (Vol. 193, p. 10). Washington, DC: American Chemical Society.
- WBA. (2018). *WBA global bioenergy statistics 2018*. World Bioenergy Association. Retrieved from https://worldbioenergy.org/uploads/181203%20WBA%20GBS%202018_hq.pdf
- Zajac, G., Szyszczak-Barglowicz, J., Slowik, T., Wasilewski, J., & Kuranc, A. (2017). Emission characteristics of biomass combustion in a domestic heating boiler fed with wood and Virginia mallow pellets. *Fresenius Environmental Bulletin*, 26(7), 4663–4670.
- Zeng, T., Pollex, A., Weller, N., Lenz, V., & Nelles, M. (2018). Blended biomass pellets as fuel for small scale combustion appliances: Effect of blending on slag formation in the bottom ash and pre-evaluation options. *Fuel*, 212(September 2016), 108–116. <https://doi.org/10.1016/j.fuel.2017.10.036>
- Zhuang, D., Jiang, D., Liu, L., & Huang, Y. (2011). Assessment of bioenergy potential on marginal land in China. *Renewable and Sustainable Energy Reviews*, 15(2), 1050–1056. <https://doi.org/10.1016/j.rser.2010.11.041>

How to cite this article: Jablonowski ND, Kollmann T, Meiller M, et al. Full assessment of *Sida (Sida hermaphrodita)* biomass as a solid fuel. *GCB Bioenergy*. 2020;12:618–635. <https://doi.org/10.1111/gcbb.12694>