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Environmental competitiveness evaluation by Life Cycle Assessment for solid fuels generated from Sida hermaphrodita biomass
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Executive Summary
As a part of a comprehensive evaluation for the use of the plant Sida hermaphrodita as a solid fuel, a life cycle assessment (LCA) according to ISO 14040/14044 was carried out by means of a suitable cradle-to-gate system design. The supply and use of chips, pellets and briquettes was studied by internal and external comparisons to show competitiveness and improvement options. The results show less differences within the Sida hermaphrodita scenarios but larger distinctions to the compared alternative biofuels such as wood pellets. As a major finding it can be stated that Sida hermaphrodita process chains result in lower environmental impacts in comparison with the alternative biofuels. The study identified impact originators and starting points for further improvement. Because there are no similar investigations on the environmental impact of Sida hermaphrodita used as a biogenic solid fuel this contribution shall give a first overview of the mentioned issues. The results so far indicate that Sida hermaphrodita provides a potentially more sustainable option for the use of biomass in combustion processes by the reduction of environmental impacts.

Keywords
Life cycle assessment, biogenic energy source, small scale combustion, biomass, perennial energy crop, solid biofuels

Contribution to Biomass & Bioenergy
I Introduction

With regard to gross final energy consumption the European Union’s share of renewable energy was 17% in 2016, which was mainly covered by biomass [Eurostat, 2018]. Striving further development of decreasing greenhouse gas emissions by 40% and increasing of the renewable energies share to 27% in 2030 compared to 1990 shows the action required [EC, 2017]. To realize these aims and to support the idea of an EU energy union in line with the 10 political priorities of the EU ([EU, 2017]; [Juncker, 2014]) a continuous improvement of technological and biomass-related characteristics (e.g. design of process modules or improvement of combustion properties) in biomass-based energy applications is required. The comprehensive evaluation of new and innovative biomass supply and its use can help to identify technologies and improvement potentials. As a significant less spread species of energy plants the woody-like non-food biomass *Sida hermaphrodita* offers the possibility of improvements for energy generation [Jablonowski et al., 2017]. As one part of a holistic approach environmental impacts of the supply and use of solid fuels can be assessed by life cycle assessment (LCA).

*Sida hermaphrodita* is part of the mallow family and has its origin in North America. In the middle of the 20th century the plant was imported to Poland where it is mainly used for energy purposes today. Without clear statistics on the European level *Sida hermaphrodita* gains currency in a magnitude of less than 1,000 ha cultivation area according to [Nahm & Morhart, 2018]. One remarkable advantage of *Sida hermaphrodita* is the possible high yield of up to 25 tDM/ha [Jablonowski et al., 2017]. Further good reasons to take a closer look at the use of *Sida hermaphrodita* as a resource for energy carrier production can be found in its benefit for the ecosystem and the low requirements regarding soil conditions, allowing extensive cultivation. Long flowering periods of *Sida hermaphrodita* provide an important source for pollinators [Borkowska, 2006], heavy metals can be absorbed in terms of soil remediation; [Borkowska, 2003], the nutrient need is low and the water demand is half as much as for willows in short rotation coppice (SRC) for example [Borkowska & Molas, 2012]. The ability to grow on marginal land allows the avoidance of the “food vs. fuel”-discussion [Nabel, 2018]. Considering alternative fertilization using digestate as a residue from biogas production, substantial *Sida hermaphrodita* biomass yields were even obtained when grown on marginal soils ([Nabel et al., 2017]; [Nabel, 2018]). In addition, calculations based on production cost data from [Kollmann, 2015] show the economic competitiveness in comparison to wood pellets for example. At the Forschungszentrum Jülich different topics like the growth of *Sida hermaphrodita* on marginal sandy soils, its symbiotic relationship with legumes such as alfalfa and lucerne, or the technical and normative usability as an energy carrier have been investigated ([Nabel, 2018]; [Nabel et al., 2016]; [Jablonowski et al., 2017]; [Kollmann, 2015]). Generated data from laboratory, greenhouse and long-lasting field studies built the basis for the life cycle inventory (LCI) and the following life cycle impact assessment (LCIA) in our study.

The focus of the presented LCA-work is on the use of *Sida hermaphrodita* as a solid energy carrier which is processed differently in form of chips, pellets or briquettes. Thresholds like those from the guidelines for pellets or briquettes ([ISO17225-6, 2014], [ISO17225-7, 2014])
and suitable equipment for the thermochemical conversion to energy are taken into consideration. Because of the fictive character of the scenarios as a whole, the assumed process chains had to be developed for each energy carrier scenario. To get a broad understanding of the observed applications an internal comparison (Sida hermaphrodita scenarios) to identify the most advantageous processing route, and an external comparison (Sida hermaphrodita and alternative scenarios) was carried out to get an idea of the environmental competitiveness. Furthermore, different sensitivity analysis were implemented and analyzed.

II Material and methods
In line with ISO 14040/14044 standards the LCA for Sida hermaphrodita was carried out including the mandatory steps of goal and scope definition, inventory analysis (LCI), impact assessment (LCIA) and interpretation ([ISO14040, 2006]; [ISO14044, 2006]). To realize the assessment step, different process chains were implemented in the LCA-Software GaBi 8.0. Information for the main (foreground) processes was taken from a project ([Jablonowski et al., 2017]; [Kollmann, 2015]), complemented by suitable literature content. Necessary data for process modules of the background processes was taken from the GaBi and ecoinvent 3 databases ([GaBi-DB, 2018]; [ecoinvent-DB, 2018]). Data for the process chains of alternative biomasses (see II.1.2) was taken from the ecoinvent 3 database.

II.1 Goal and scope
Goal of this study is the comparison of environmental impacts of three different processing routes for Sida hermaphrodita biomass used as a solid fuel in two different ways. The implementation of different scenarios for the use of Sida hermaphrodita as a feedstock for solid fuel allows to identify the most advantageous processing route by an internal comparison of impacts. Additional aims of the study can be termed with estimation of environmental competitiveness and generation of information for potential stakeholders (e.g. farmer or energy carrier user) by an external comparison of environmental impacts (e.g. climate change). Furthermore, improvement potentials shall be detected for each processing route.

Therefore three different scenarios were developed describing the different pathways of Sida hermaphrodita biomass. The following described scenarios (see II.1.1) are for the production and use of chips (scenario SI), pellets (scenario SII) and briquettes (scenario SIII). The generated LCIA results are compared to results from established conventional process chains for the use of woody biomass (see II.1.2).

II.1.1 Sida hermaphrodita Scenarios
The process chains for scenarios SI, SII and SIII are set as cradle-to-gate systems. All essential steps from the biomass production to the combustion stage, including ash disposal were considered. The three developed and implemented Sida hermaphrodita process chains consisted of five process stages as shown in Fehler! Verweisquelle konnte nicht gefunden werden.
Figure 1: Simplified structure of process chains with five process stages for the supply and use of Sida hermaphrodita as a solid fuel in scenario SI (chips), SII (pellets) and SIII (briquettes)

The system starts with the process stage of biomass production containing the same process modules in all scenarios but with different quantitative characteristics, depending on the considered lower heating values, biomass losses etc. Processes include actual applications like harrowing or fertilizing, their energy demands (e.g. diesel or electricity) and manufacturing as well as the production or supply of necessary material like fertilizer or water. Thus, this stage contains the tillage of the farmland, the planting of seedlings and related preparations (plant protection) and the fertilization during growth phase. Afterwards the chopping of the *Sida hermaphrodita* biomass is realized like for corn harvest using a conventional corn shredder. The implemented scenarios also consider all related transports of machinery and biomass with a distance of 5 km in maximum.

Because of different processing variants like chip production, pelletization or briquetting the structure of the production and processing stage differs in all scenarios. The storage and natural drying in scenarios SI, SII and SIII is taken into account by a scenario specific building structure. The internal transport of raw material is assumed to be performed by agricultural standard equipment (tractor). It is assumed that the processing of raw *Sida hermaphrodita* material (chips) to pellets or briquettes is performed by mobile technical units, while their mobility is considered with a distance of 50 km in maximum. Besides the transport of the technical units, the specific process modules are considered by their energy demands for operation and proportionate production of the machinery. The pelletization unit is assumed with a throughput of ca. 350 kg/h and a related energy demand of 15 kW. Performance data of the briquetting unit is given with a throughput of 300 kg/h and an energy demand of 22 kW.
The products storage (e.g. silos), logistics and infrastructure are varied for the storage and shipping stage. Included activities are the production and operation of storage facilities as well as internal transports. Due to the different types of intermediate products (chips, briquettes, pellets) scenario specific technical equipment is required. Internal logistics are realized by agricultural machinery for scenario SI, screw conveyors for SII and fork lifter for SIII. The storage facilities are implemented by suitable buildings (chips, briquettes) or silos (pellets) as well as a proportionate electricity use.

The combustion stage includes activities like electricity supply for the operation of the users’ storage facility in addition to the furnace operation and its production. The different types of *Sida hermaphrodita* intermediate products (chips, pellets, briquettes) also affect the combustion stage, which is distinguished by the performance class of the used small-scale furnaces. The combustion of chips in scenario SI was implemented by a 50 kW furnace originally designed for wood chips. Scenario SII contains a 25 kW furnace designed for wood pellets while scenario SIII uses a 30 kW furnace originally constructed for wood logs. The furnace’s datasets do not only cover the given number but a specific range lower than 100 kW. The use of different performance levels reflects practical tests with small scale furnaces [Jablonowski et al., 2018].

In the last step, the ash disposal process as treatment of ash is included in all scenarios. In every case “disposal by household waste” is assumed due to the performance class of < 100 kW [DEPI, 2016]. This stage is implemented by an ash disposal via incineration of household waste and via sanitary landfill. As a basis for the general process development, a basic scenario of a *Sida hermaphrodita* cultivation area of 4 ha harvested for one time was assumed. This determination plays a crucial role for the design of process modules (e.g. dimensioning of pelletization or storage).

### II.1.2 Process routes for alternative biomass

Datasets for alternative biomasses and their process chains were taken from the ecoinvent database. Due to limited availability, considered datasets were referred to wood-related energy carriers only. The compared alternative scenarios represent energy carriers like wood chips, wood pellets and wood logs. The considered data include all process stages from biomass production to the energy carrier usage by combustion and included ash disposal. The performance classes are in the same magnitude like the *Sida hermaphrodita* scenarios SI, SII and SIII. Considered process stages are “the infrastructure, the wood requirements, the emissions to air, the electricity needed for operation, and the disposal of the ashes” [Bauer, 2017].

To ensure the comparability in relation to the technical key data, only selected datasets (performance reference < 100 kW) were utilized for the comparative process. The performance of the included furnaces ranges between 25 and 50 kW. In most cases available state-of-the-art processes (SOTA, 2014) with relation to Switzerland (CH) or the rest of the world (RoW) are considered because these datasets represent the process chains with the lowest impacts within the available database.
II.1.3 Functional unit and relation

The functional unit (FU) is the supply of 100 GJ thermal energy from the considered particular energy carriers (chips, pellets, briquettes), representing the final energy demand for approx. 550 m² living space of a newly constructed apartment building (7 flats) according to [EnEV, 2015]. The geographical system boundaries in relation to the used data are drawn at European or German level and the time relation of all used data is not older than 2015 if possible.

To realize the valuation of environmental impacts the LCIA-method of the International Reference Life Cycle Data System (ILCD) which includes 16 impact categories was used [EC-JRC, 2010]. Additionally, a normalization was performed with the method of Product Environmental Footprint (PEF Pilot 1.09) which refers to the EU-27 and includes the biogenic / non-fossil carbon emissions [EC, 2013]. The unit of the output is presented in person equivalents (PE).

II.1.4 Life cycle inventory

The main inputs of the Sida hermaphrodita scenarios SI, SII and SIII were the biomass (SI = 7,660 kg/FU; SII = 7,130 kg/FU; SIII = 7,530 kg/FU) and water (SI = 2,853 m³/FU; SII = 3,107 m³/FU; SIII = 3,213 m³/FU). Further inputs were fertilizer (92.8 - 99.8 kg/FU), direct electricity use (1.0 - 2.6 MJ/FU) and further energy resources (13.6 - 18.6 MJ/FU). The intermediate products of each scenario were chips in SI (6,200 kg/FU), pellets in SII (5,811 kg/FU), and briquettes in SIII (6,274 kg/FU). Besides the main process output of 100,000 MJ/FU thermal energy, outputs can be named as biomass loss (645 - 897 kgDM/FU) and ash (127.1 – 225.2 kg/FU).

III Results and discussion

III.1 Internal comparison

To identify the most advantageous processing route for Sida hermaphrodita the results of the LCIA can be ranked by single values for specific categories. In Fehler! Verweisquelle konnte nicht gefunden werden. it is shown that the results of categories like “Climate change, incl. biogenic carbon (CC incl)” or “Ozone depletion (OD)” are very similar with a view on the magnitude while other impact categories like “Acidification (AC)” or “Eutrophication, terrestrial (ET)” vary widely. The factors between the largest and lowest value per impact category ranged from 1.1 to 5.3.

To get the possibility of a comparison between the scenarios which summarizes all 16 impact categories, the LCIA results were transformed into normalized values by the mentioned ILCD method. The absolute normalized values of the implemented scenarios SI, SII, and SIII demonstrated that the impacts differ by less than 5 %, making it difficult to see a clear winner in one of the scenarios.
Figure 2: Results of the LCIA for scenarios SI, SII and SIII per impact category according to ILCD in specific equivalents

- Human toxicity midpoint, cancer effects (HT CE)
- Ecotoxicity freshwater (ET Fw)
- Resource depletion, mineral, fossils and renewables (RD mfr)
- Human toxicity midpoint, non-cancer effects (HT nCE)
- Climate change midpoint, incl. biogenic carbon (CC incl)

These largest impact categories range in a magnitude between 8 % (CC incl in SII) and 32 % (HT CE in SI) share per category. Main cause for the impacts can be named exemplary by the furnace production in the categories “ET Fw” and “HT CE” or by the fertilizer production in the impact categories “HT nCE” and “RD mfr”. The main cause for the large impact of the category “CC incl” can be found in the activity of combustion. It has to be remarked that this large impact is mainly associated with biogenic CO$_2$, so that an LCIA method excluding biogenic carbon dioxide would lower the impact substantially. It can be stated that the basic distribution of the category shares is very similar for all scenarios. Significant differences can be identified with the “HT CE” category in scenario SII and the “RD mfr” category in scenario SIII. These distinctions can be traced back to the impact of single process modules. While the “HT CE”
category is influenced by different furnaces and their specific impact the “RD mfr” category differs by the influence of the storage facilities and equipment.

The differences between the considered scenarios are also reflected by the results of the relative share of PE for the sum of all 16 impact categories per process stage (Fehler! Verweisquelle konnte nicht gefunden werden. (upper graph)). In principle the process stages “biomass production” and “combustion” represent the largest impact originators. Anomalies within the upper graph can be identified with the small share of the storage and shipping and the ash disposal stage in scenario SI. The first discrepancy can be justified by minimized technical efforts for chips processing, while the ash disposal is simply lower due to less ash content of Sida hermaphrodita chips.

The lower five graphs represent the complexity of the impacts caused by separate process stages. For example, as shown in Fehler! Verweisquelle konnte nicht gefunden werden. the ash disposal stage has nearly no influence on the “HT CE” category but on the “ET Fw” category. As mentioned before, the large impact of the combustion stage is caused by biogenic carbon dioxide which has to be credited in an LCIA excluding biogenic carbon dioxide.

The presented setting of scenarios shows no significant differences between scenarios SI, SII, and SIII. However, the closer look into impact category and process stage specific relative PE-shares reveals focal points of impacts’ origins. These can be used as starting points for technology or biomass related possibilities for process improvement. It is noteworthy that not all process modules can be influenced. On the one hand it is possible to minimize the influence of fertilizer production by minimizing its application but on the other hand furnace production
cannot be influenced. Moreover, based on the discussed results an impact category depending optimization (e.g. carbon dioxide reduction) can be initiated. In relation to the assessment of single process stages similarities with other alternative process chains can be stated. Other studies like [Ruiz et al., 2018] or [Fantozzi & Buratti, 2010] have also shown largest impacts in the process stage “biomass production” but also in pelletization or briquetting. To improve the results by getting clearer separation between the scenarios the change of goal and scope characteristics can be used. One basic possibility is the relocation of the system boundaries to intensify and identify significant differences. Another option would be the consideration of temporal developments for activities in the biomass production stage as described in [Fantozzi & Buratti, 2010] in relation to SRC for example. Furthermore, the effects of a change in the “general scenario” (e.g. larger cultivation area as design base) should be analyzed.

Figure 4: relative shares of PE per process stage for scenarios SI, SII and SIII; for the sum of all impact categories (upper graph) and for largest impact categories (lower graphs)

III.2 External comparison
The comparison with alternative woody biomasses (e.g. wood pellets) showed that the impact categories’ values of most compared wood alternatives are larger than those of Sida hermaphrodita scenarios. In Fehler! Verweisquelle konnte nicht gefunden werden. scenario SI is set to 100 % for two different routes, which differ by the ash disposal (=AD) processing stage
(option ADI: incineration route, option ADII: landfill route). With option ADI only one process chain “wood pellets, state of the art” is able to undercut the Sida hermaphrodita system by 1.6%. The other ash disposal route changes the relative PE values in a way that Sida hermaphrodita scenarios SI and SII show better values than the alternative in every case. The study of such a relation can also be used for initiation of optimization.

Figure 5: Comparison of relative PE values for Sida hermaphrodita scenarios SI, SII, and SIII as well as 8 different wood scenarios with different ash disposal options

It can be stated that there is a large variety in impact categories but some of the presented results (e.g. wood pellets, 25 kW, SOTA or mixed logs, 30 kW, SOTA) are close to the Sida hermaphrodita results. In general, a significant advantage for Sida hermaphrodita can be observed. An even better and clearer accentuation of the scenarios SI, SII and SIII would be given by a comparison with the available non-SOTA and non-Swiss-related datasets for woody energy carriers (not shown). For further research it is necessary to design and refine the process structure of prospective compared datasets. Eligible comparable biomasses and their routes can be named with corn or Miscanthus for example ([Xue, 2016], [Moitzi, 2014]). To provide information on the most charged emission pass (air, soil, water) the analysis of these shares could be realized and compared with further biomass like shown in [Itten, 2011].
III.3 Influencing factors - Variation of yield

The influencing factors along the Sida hermaphrodita process chains were studied in different respects. As mentioned in the previous section III.2, the modification of ash disposal routes leads to findings of their specific influence to the whole process. Another possibility for investigating influences is the aspect of sensitivity. The variation of the specific harvesting yields is exemplary presented in Fehler! Verweisquelle konnte nicht gefunden werden. for scenario SII (pellets). The graph demonstrates the relative PE in dependence from the harvesting yield and the related area needed per FU. The value of 439 GJ/ha represents the base for calculations and thus the related PE-value of the previous sections III.1 and III.2. This PE-value was set to 100 %. The grey colored bar marks the range of relative PE-values from the shown wood-based datasets. It can be stated that also lower yields (down to 100 GJ/ha, dashed line) led to competitive PE-values, depending on alternative processes to compare. By taking a look at the dependence between the characteristics of yield and related harvesting area from the PE-values a non-linearity of the parameters was identified. It can be stated that the ratio PE to needed area gets lower with decreasing yield per FU. Furthermore, a reduced yield by 50% (e.g. 400 GJ/ha to 200 GJ/ha) does not lead to a doubled amount of PE.

![Graph showing relative PE-value for SII process chain (pellets) in dependence of varying yields and the related cultivation area per FU](image)

Figure 6: relative PE-value for SII process chain (pellets) in dependence of varying yields and the related cultivation area per FU

Further studies on the influencing factors of scenario specific modules or parameters can be realized by the change of specific process modules within the different process stages (e.g. production of processing machinery) or the variation of machinery throughputs. As mentioned in chapter III.1, the variation of system boundaries should be analyzed. As possible and maybe desirable effects of these relocations the reduction of background process modules’ (e.g. furnace production) influence could be minimized.
IV Conclusions

An internal comparison of different production/processing pathways does not show considerable differences in their overall environmental impacts. External comparisons with alternative woody biomass have shown beneficial properties of *Sida hermaphrodita*. Analyses of changeable process modules (e.g. disposal route) show starting points for process improvement. Depending on process modules not all impact causer are accessible for further improvement (e.g. furnace production). The ecological competitiveness is also given with lower yields of *Sida hermaphrodita* biomass. Moreover, task definitions for future (e.g. comparison *Miscanthus*) work could be identified. Summarizing, results suggest *Sida hermaphrodita* solid biofuels as a useful alternative to established solid biofuels.

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VI References

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journal article


Systems Analysis and Technology Evaluation at the Research Centre Jülich

Many of the issues at the centre of public attention can only be dealt with by an interdisciplinary energy systems analysis. Technical, economic and ecological subsystems which interact with each other often have to be investigated simultaneously. The group Systems Analysis and Technology Evaluation (STE) takes up this challenge focusing on the long-term supply- and demand-side characteristics of energy systems. It follows, in particular, the idea of a holistic, interdisciplinary approach taking an inter-linkage of technical systems with economics, environment and society into account and thus looking at the security of supply, economic efficiency and environmental protection. This triple strategy is oriented here to societal/political guiding principles such as sustainable development. In these fields, STE analyses the consequences of technical developments and provides scientific aids to decision making for politics and industry. This work is based on the further methodological development of systems analysis tools and their application as well as cooperation between scientists from different institutions.

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