RESEARCH REVIEW

Virginia mallow (Sida hermaphrodita (L.) Rusby) as perennial multipurpose crop: biomass yields, energetic valorization, utilization potentials, and management perspectives

MICHAEL NAHM and CHRISTOPHER MORHART
Chair of Forest Growth and Dendroecology, Albert Ludwigs-University Freiburg, Tennenbacher Str. 4, Freiburg 79106, Germany

Abstract

This article reviews the scholarly literature dealing with the perennial multipurpose crop Virginia mallow (Sida hermaphrodita (L.) Rusby; Sida in the following). In regions dominated by intensive agricultural management practices, growing Sida holds the potential to combine ecosystem services such as decreasing soil erosion, reducing nitrate leaching as well as enhancing biodiversity, with economic profit for the farmer. After promising biomass yields of Sida were reported from studies performed in Poland about 15 years ago, the interest in this plant species has continuously increased, and different utilization pathways were examined, predominantly by researchers in Poland and Germany. At present, however, a comprehensive overview that summarizes the different lines of research performed regarding the use of Sida is lacking. This review aims at closing this gap. After providing background information on Sida, we summarize the main results obtained from investigations concerning biomass yields, fertilization effects, key findings concerning direct combustion, biogas production, steam gasification, phytoremediation, and alternative utilization pathways. Thereafter, we highlight important aspects of Virginia mallow cultivation practices, including first estimates regarding the costs involved. Finally, we point to existing research gaps. Summarizing the available literature on Sida, we aim at raising the interest of scientists and farmers in this plant species further and to show where future research might tie in with, as the successful cultivation of Sida might represent a worthwhile strategy to transform current agricultural practices in Central Europe into approaches that are more sustainable and resilient against future challenges.

Keywords: biodiversity, biogas, combustion, renewable energy source, Sida hermaphrodita, sustainable agriculture, Virginia mallow

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Introduction

Challenging and competitive market conditions in the European bio-economy lead to increasingly intensified agricultural cultivation practices that typically involve monoculture management. However, these practices entail ecologically adverse effects as exemplified by nitrate leaching, excessive soil erosion, as well as the die-back of insects and birds in agriculturally dominated areas (Montgomery, 2007; Beketov et al., 2013; Goulson, 2013; Benoit et al., 2014; Thomas, 2016; Hallmann et al., 2017; Heldbjerg et al., 2017). To countersteer these developments and to improve the resilience of agricultural systems, the diversification of crops and the (re-) creation of habitat heterogeneity seem indispensable (Benton et al., 2003; Lin, 2011). Decision-makers of the European Union have recognized these trends and aim at supporting new approaches that combine economically profitable with ecologically valuable farming. As a consequence, a new subsidy framework that includes Greening measures was set up (European Parliament and Council, 2013). Similarly, an increasing number of farmers are open to testing and growing alternative crops such as short rotation coppice (SRC), or other perennial plants such as Miscanthus ssp., Virginia mallow (Sida hermaphrodita (L.) Rusby; hereafter referred to as Sida) and cup plant (Silphium perfoliatum L.), as alternative to well-established energy crops like maize.

Whereas SRC and Miscanthus have amply been discussed in the literature dealing with the cultivation of
perennial agricultural crops (Bilandzija et al., 2017; Georgiadis et al., 2017; Hauk et al., 2017; Maddison et al., 2017; Schweier et al., 2017), publications concerning Sida and cup plant are rarer and scattered, although the scientific interest in growing and utilizing Sida has grown considerably during the last decades. Chiefly, this interest is driven by the necessity to find commercially and ecologically attractive biomass sources for alternative pathways of energy production (e.g. Borkowska & Molas, 2013; Stolarski et al., 2014a; Michalska et al., 2015; Nabel et al., 2016; Wierzbowska et al., 2016; Jablonowski et al., 2017; Werle et al., 2017), but Sida offers also other interesting utilization perspectives for the European bio-economy. In the 1930s, the plant was first studied in Eurasia by botanists in the former Soviet Union to assess its utilization potentials as soil stabilizer, fodder crop, honey plant, and fiber plant for the pulp and paper industry (Spooner et al., 1985). In 1955, it was introduced into Poland (Borkowska et al., 2006a), the country in which most of the research activities on Sida were conducted until today. Currently, more than 300 ha (750 acres) of Sida plantations are managed in Poland, which is more than in any other European country (Igieński et al., 2015). In Germany, Sida is cultivated on approximately 100–150 ha that comprise experimental field sites, and plantations for seed production as well as for energetic consumption of the biomass (Reent Martens, personal communication, October 27, 2017). In a small number of other European countries, such as Austria, Hungary, and Lithuania, it is grown on only a few hectares. Nonetheless, managing perennial plants such as Sida bears several advantages for farmers – provided, it is also attractive from an economic perspective. It reduces the workload because working steps needed for annual crop cultivation like plowing and harrowing are no longer necessary, it ensures a continuous ground cover, and, in the case of Sida, the crop biomass can be harvested with conventional harvesting techniques and stored without problems. The latter represents an advantage compared to harvesting woody biomass from SRC which is also shared by Miscanthus spp. cultivation. Yet, due to the high share of problematic elements such as chlorine and potassium that affect the boiler interior by causing corrosion and slagging (Baxter et al., 2014; Jensen et al., 2017), Miscanthus spp. can only be burnt in expensive special steel burners, whilst Sida chips can be burnt in any heating plant, rendering it a particularly interesting energy crop.

In particular during the last decade, an increasing number of researchers from predominantly Poland and Germany realized the potential of Sida as an ecologically valuable raw material for various utilization pathways, and investigated it from a variety of research perspectives. Hitherto, however, a comprehensive overview on the different lines of research pursued and on Sida’s possible utilization pathways is lacking. In the present article, we will present such an overview on the scholarly literature dealing with Sida. We will also highlight aspects of its cultivation and point to current gaps in knowledge and further research questions. The sources compiled in this review were retrieved via internet search engines (Web of Science, Google Scholar, Google), using the key words ‘Virginia mallow’ and ‘Sida hermaphrodita’ plus related formulations, and by tracing literature cited in retrieved publications. To cover as many relevant publications from the year 2000 onward as possible, a special focus was put on taking also less known Polish sources into account. Only full papers and book sections were considered in this review, oral and poster presentations were disregarded.

Origin and ecology traits of Sida hermaphrodita

The common name for Sida is Virginia mallow or Virginia fanpetals, referring to its origin in Northern America. However, Sida is hardly found in Virginia, and its main area of distribution is located in the adjacent states to the west and north. Botanically, the genus Sida belongs to the Malvaceae family, hence the reference to mallow in one of its common names. It thrives on moist but opens to partially shaded habitats on riverine terraces and floodplains, including disturbed situations along railroad banks and road sides (Spooner et al., 1985). Due to its specific habitat preferences, Sida is considered a rare species in its natural range of distribution. It is a perennial herb with shoots that emerge in April from a well-developed rhizome, its buds being situated at the base of the stems of the previous year. It seems likely that Sida reproduces both sexually via seed germination, but also asexually via spreading rhizomes (Environment Canada, 2015). In general, during an estimated plantation life time of 20 years, Sida is deemed rather insusceptible toward pests and diseases, although it can be affected by Sclerotinia sclerotiorum (Haller & Fritz, 2015; Remlein-Starosta et al., 2016). It can withstand temperatures of up to −35 °C without problems (Borkowska et al., 2006b). Still, Sida can be considered a thermophilous species in Central Europe (Franzaring et al., 2015), and although it is generally considered resistant to temporary droughts (Smoliński et al., 2011), its growth performance appears to react more sensitively to reductions of water availability than other non-woody energy crops (Jankowski et al., 2016).

Sida flowers abundantly, from July onwards until the first frost, thus providing ample pollinator food. It can yield up to 120 kg honey per hectare (Borkowska et al., 2006a). But not only insects seem to profit from Sida. In
a study in which the number of earthworms and their total biomass were determined in the soil under seven different perennial crops including *Sida* and maize, both parameters reached their maximum under *Sida*, thus pointing to its potential to valorize also the soil ecologically (Emmerling, 2014). Although *Sida* produces similar amounts of biomass as SRC, its water demand amounts to only half of the water demand of woody short rotation crops such as willow (Borkowska & Molas, 2012). Moreover, compared to barley and potato, it did not influence the soil moisture content significantly (Cetner et al., 2014). In general, perennial crops such as SRC, and thus, flowering *Sida* plants in particular, can be expected to reduce soil erosion and nitrate leaching, to improve the soil quality, to increase biodiversity, and to upgrade the landscape experience for people in open arable settings (Butler Manning et al., 2015). *Sida* can grow more than 4 m in height within one vegetation period and is able to develop more than 40 shoots per square meter (Borkowska & Molas, 2012). In short, *Sida* can be expected to generate a variety of ecosystem services, whilst simultaneously producing considerable amounts of utilizable biomass under favorable growth conditions.

**Biomass productivity**

In the year of the establishment of a plantation, the biomass yield of *Sida* is typically low. In the second or third year, it increases considerably. Nevertheless, this increase depends on the soil and weather conditions, fertilizers applied, and careful weed control. It might also depend on the method chosen for the establishment, using seeds, seedlings, and root cuttings. In general, root cuttings seemed to result in the highest biomass productivity (Borkowska & Molas, 2012; Tworkowski et al., 2014). Table 1 contains an overview of average biomass yields obtained in different studies performed after the year 2000. Where possible, the first two years of growth were excluded from the determination of these yields. *Sida*’s annual biomass productivity ranked between 8.7 and 20.3 tons of dry matter per hectare (t$_{dm}$ ha$^{-1}$). In most cases, the annual yield of *Sida* exceeded 10 t$_{dm}$ ha$^{-1}$ after the first two years of growth. However, the biomass yields presented in Table 1 were determined after harvesting operations that were performed in different months of the vegetation dormancy, ranging from October (Slepetys et al., 2012) until February (Tworkowski et al., 2014). Because *Sida* plants still may have leaves until November, such differences impede the direct comparison between the determined biomass yields. Consequently, Jablonowski et al. (2017) recommended the use of a BBCH-*Sida* development code created by their research group which facilitates a direct comparison of biomass yields in relation to different developmental stages of *Sida* plants throughout the year. Regarding the comparison with other perennial energy crops, the amounts of dry biomass given in Table 1 rank in the same dimensions like that of other solid fuel feedstock plants such as SRC and Miscanthus. In direct experimental comparisons, *Sida*’s biomass productivity exceeded that of willow clones considerably (Borkowska & Molas, 2012, 2013) and produced also higher amounts of dry matter compared to Miscanthus (Slepetys et al., 2012). In other studies, its biomass yield was lower compared to that of Miscanthus (Kuś et al., 2008; Borkowska & Molas, 2013) and that of willow (Kuś et al., 2008). These findings signify that *Sida*’s biomass productivity is dependent on soil and climate characteristics, but in general, it can compete well with better known and already established energy crops.

**Effects of fertilization**

In most field studies covered in Table 1, the tested plants were fertilized, often using a mixture of nitrogen, phosphorous, and potassium. In general, nitrogen fertilization increased the biomass yield of *Sida* in these studies. This effect seems to be due to an increase in shoot height, shoot diameter, and number of shoots per square meter (Borkowska et al., 2016). Positive responses to NPK fertilization as well as to liming were observed from *Sida* grown on acidic soil in Lithuania (Siaudinis et al., 2015, 2017a). Still, the biomass yields of *Sida* remained rather low in these studies even on the fertilized plots, and their average amounted to 6.6 t air-dry mass across all treatments for three years of growth. Yet, both nitrogen fertilization and liming of *Sida* significantly increased the C content in the 0–30 cm soil layer (Siaudinis et al., 2017b). However, in some studies, the nitrogen fertilization did not affect the biomass yield significantly (Borkowska et al., 2009). Higher doses of phosphorus tended to significantly raise *Sida* yields (see Table 1), but again, exceptions have been reported (Borkowska et al., 2009, 2015).

Other studies using potted plants focused on assessing the suitability of digestate from biogas plants as fertilizer for *Sida*. The application of this digestate resulted in significantly increased *Sida* biomass production (Barbosa et al., 2014; Nabel et al., 2014, 2016). Because the utilization of digestate was associated with significantly lower amounts of nitrate leaching compared to NPK fertilization, its application offers a promising method of fertilizing fields with an ecologically more valuable growth stimulant than mineral NPK fertilizers (Nabel et al., 2016). In other experiments, different properties of *Sida* were analyzed after application of sewage sludge as fertilizer. These include parameters related to *Sida*’s photosynthetic apparatus efficiency (Augustynowicz...
et al., 2010; macroelement contents (Krzywy-Gawrońska, 2012a), but also heavy metal and other element contents in Sida biomass (Borkowska & Wardzinska, 2003; Krzywy-Gawrońska, 2012b; Wierzbowska et al., 2016) as well as in ashes (Kacprzak et al., 2010).

The use of Sida as biofuel: biophysical and biochemical properties

Properties of Sida biomass regarding thermal conversion

Until today, the greatest interest in Sida lies in its potential to be used as a regenerative energy source. Hence, Sida was frequently investigated regarding its thermo-physical and biochemical properties in the context of direct combustion and biogas production. When used as solid fuel, parameters often determined are the higher heating value (HHV) and the lower heating value (LHV). In ten studies considered in this review, the HHV of Sida ranked between 16.5 and 19.5 MJ kg\(^{-1}\) dry matter at an average of 18.4 ± 0.9 MJ kg\(^{-1}\) dm; the LHV between 14.0 and 17.2 MJ kg\(^{-1}\) dm at an average of 16.1 ± 1.2 MJ kg\(^{-1}\) dm (Borkowska et al., 2009, 2016; Wróblewska et al., 2009; Smolinski et al., 2011; Szyszlik-Bargłowicz et al., 2012; Stolarski et al., 2013, 2014a; Franzaring et al., 2014; Table 1}

| Source name | Fertilization (kg ha\(^{-1}\)) | Plant density (Thousand * ha\(^{-1}\)) | Year of establishment | Years of veg. periods covered | N | P | K | Seeds | Seedlings | Root cuttings | Yield (tdm ha\(^{-1}\)) |
|-------------|-----------------------------|-----------------------------------|----------------------|-------------------------------|---|---|---|-------|------------|---------------|-------------------|-----------------|
| Borkowska et al. (2016) | 2003 | 2005-2007 | 100 | 40 | 80 | 250 | 11.8 |
| Borkowska & Molas (2013) | 2003 | 2006-2008 | 100 | 35 | 83 | 3 | 17.6 |
| Borkowska & Molas (2012) | 2003 | 2005-2007 | 100 | 35 | 83 | 250 | 13.0 |
| Borkowska et al. (2009) | 2003 | 2005-2007 | 100 | 35 | 83 | 250 | 11.0 |
| Borkowska & Molas (2016) | 2003 | 2005 | 120 | 90 | 120 | 41 | 20.3 |
| Kuś et al. (2008) | 2004 | 2005-2006 | 75 | 50 | 75 | 10 | 10.1 |
| Slepetyś et al. (2012) | 2007 | 2010-2011 | 0 | 0 | 0 | 20 | 10.5 |
| Tworkowski et al. (2014) | 2009 | 2011-2012 | 50 | 20 | 50 | 375 | 11.2 |
| Haller & Fritz (2015) | 2011 | 2013-2014 | 180 | 0 | 0 | 125 | 8.7 |
Tworkowski et al., 2014; Siaudinis et al., 2015; Jablonowski et al., 2017). Whilst the HHV of *Sida* biomass appeared to be rather constant from November until April in one study, the LHV increased from 9.7 to 15.0 MJ kg\(^{-1}\) within this time span (Stolarski et al., 2014a), presumably owing to the changing water content of the biomass.

Similarly, the amount of crude fibers in *Sida* biomass was strongly correlated with an increase of the HHV (Siaudinis et al., 2015), which is lower during the vegetation period when the *Sida* plants have leaves and flower. The amount of neutral detergent fibers (NDF; cellulose, hemicelluloses, and lignin) in *Sida* material harvested during the flowering stage accounted for 60.2 % of dry matter (Pokój et al., 2015), whilst it amounted to about 80 % when cut in October (Slezetys et al., 2012). It even reached 88.1 % in another study, in which, however, the time of harvest was not given (Michalska et al., 2015). In accordance with these findings, the contents of cellulose and lignin in the stems remained rather stable from June until December, whilst they increased during that time in the leaves (Jablonowski et al., 2017).

Also, the ash content of field-grown *Sida* varies throughout the growing season, but typical ash contents of *Sida* analyzed after harvesting between November and March fluctuated around 3 % of dm (e.g., Stolarski et al., 2014a; Jablonowski et al., 2017), ranging from 2.5 % (Tworkowski et al., 2014) to 4.2 % (Kacprzak et al., 2010). The latter source showed in addition that the ash content of *Sida* depended on the type and the amount of fertilizer applied. The ash high melting point of *Sida* exceeded 1500 °C in one study, presumably because of its relatively high contents of CaCO\(_3\) and other molecules that only melt at high temperatures, and the simultaneous presence of only very few low-melting potassium silicate compounds (Jablonowski et al., 2017).

The water content of *Sida* stems determined in November can still exceed 40 % of dm (Stolarski et al., 2014a). In January and February, at harvesting time, it can be expected to amount to 20–25 % of dm (Stolarski et al., 2014a; Tworkowski et al., 2014), and it can drop to about 10 % in March and April (Lisowski et al., 2011; Jablonowski et al., 2017).

Several authors assessed the content of elements in *Sida* dry matter, digestates, or ashes (Szyszklak-Bargłowicz & Piekarowski, 2009; Kacprzak et al., 2010; Barbosa et al., 2014; Stolarski et al., 2014a; Szyszklak-Bargłowicz, 2014; Siaudinis et al., 2015; Wierzbowska et al., 2016; Jablonowski et al., 2017). For example, carbon contents of *Sida* biomass remained rather constant from December until April, fluctuating around 49 % of dm (Stolarski et al., 2014a). Values for the carbon content in two other studies amounted to 45.9 and 47 %, and the nitrogen content to 0.3 and 0.2 %, respectively (Wróblewska et al., 2009; Michalska et al., 2015).

In sum, the chemical composition of *Sida* is considered favorable for combustion in comparison with herbaceous biomass (Siaudinis et al., 2015), and problems related to ash melting such as slagging or bed agglomeration are expected to be negligible, as *Sida*’s combustion properties seem similar to those of woody biomass (Jablonowski et al., 2017).

Regarding the energy expenses and energy yield of *Sida* cultivation, Siaudinis et al. (2015) performed a comparative analysis. Depending on the time of the year, *Sida*’s energy output amounted to 105 GJ ha\(^{-1}\), whilst that of cup plant reached 236 GJ ha\(^{-1}\). In another study, Jankowski et al. (2016) determined an energy yield of *Sida* that reached 152 GJ ha\(^{-1}\), and it was considerably lower than that of other crops tested, such as Miscanthus and maize. The energy yields determined for *Sida* by Siaudinis et al. (2015) and Jankowski et al. (2016) are much lower than that determined by Jablonowski et al. (2017), who reported 440 GJ ha\(^{-1}\). This difference can be attributed to the considerably higher yield at the site studied by Jablonowski et al. (2017). The *Sida* dry matter yield per hectare that resulted in 440 GJ ha\(^{-1}\) was 23.4 t\(_{\text{dm}}\) ha\(^{-1}\), whilst it amounted to only 6.2 t ha\(^{-1}\) air-dry mass across all treatments in the study of (Siaudinis et al., 2015), and to 8.2 t\(_{\text{dm}}\) ha\(^{-1}\) as an average of three years, when in addition, the biomass was harvested already during summer (Jankowski et al., 2016).

**Pellets, briquettes, and steam gasification**

Because the harvested *Sida* biomass occupies large volumes when stored, it was also tested as pellets and briquettes. Lisowski et al. (2011) compared the specific density of processed *Sida* biomass to Miscanthus biomass and found that only *Sida* matched the density requirements for pellet or briquette production of more than 650 kg m\(^{-3}\), reaching at least 1094 kg m\(^{-3}\). Similarly, when comparing *Sida*’s biomass properties to that of cup plant, Siaudinis et al. (2015) found that only *Sida* met the requirements for pellet production. These pellets were made from biomass harvested in September and October and had a comparably high ash content of 6 % (Siaudinis et al., 2015), which indicates again that *Sida* should better be harvested after the turn of the year. In another case study, the ash content of *Sida* pellets amounted to only 2.9 %, but it was not specified when the biomass was harvested (Szyszklak-Bargłowicz, 2015). In this study, the emission properties of *Sida* pellets were compared to those of willow pellets when being burnt in a typical low-power furnace used for wood pellets in one-family houses. In most parameters assessed, both pellet types performed similarly. Only
with regard to CO and dust, the emission of Sida pellets exceeded that of willow considerably. This effect, however, was attributed to an incomplete combustion process, as the raw surface of Sida pellets caused blockings in the flow of the material supply to the burner (Szyszłak-Bargłowicz, 2015). This shows that systems designed for wood pellet combustion might require technical adjustments when pellets from raw materials other than wood are used.

As for briquettes, the process of briquetting Sida required the highest consumption of energy in comparison with Miscanthus sacchariflorus and Spartina pectinata, but it also displayed the highest mechanical durability (Kowalczyk-Jusko et al., 2011; Stolarski et al., 2013). Analyzing Sida shoots harvested in March and stored outside until end of August, Stolarski et al. (2013) determined the LHV of the biomass used for briquetting at 16.9 MJ kg\(^{-1}\), and for the briquettes at 16.6 MJ kg\(^{-1}\). The respective ash contents were 1.9 and 2.8 % of dry matter. However, Sida briquettes were generally of lower quality than briquettes made from woody biomass.

Moreover, Sida’s biomass properties when processed via the innovative approach of steam gasification were analyzed. In comparison with willow and four other nonwoody plant species, Sida’s biomass char reactivity for 50 % of carbon conversion was highest at all three temperatures tested. The produced gas volume was, however, rather similar in all nonwoody crops, but it was slightly lower for willow, which also displayed the lowest reactivity, at the highest reaction temperature of 800 °C (Howaniec & Smoliński, 2011). Nevertheless, the sample reactivity of renewable biomass species including Sida was negatively correlated with the total gas yield produced in the gasification process, that is, samples consisting of lignite from opencasts and of hard coal from coal mines produced more gas. In the case of hard coal, the obtained gas volume per kg was more than twice as high as that of biomass plants (Smoliński et al., 2011). Because cogasification of different fuel materials was found to hold the potential to increase the total gas volume output compared to that of two fuels tested separately, Sida biomass and Miscanthus biomass were mixed with ground coal in another experiment. Indeed, such a synergetic increase in the total gas production was observed in the co-gasification of these fuels, and it was more pronounced in the fuel blend containing Sida biomass compared to that containing Miscanthus (Smoliński & Howaniec, 2017).

Sida’s suitability for biogas production

In several studies, Sida was also investigated with regard to its suitability for biogas production. Oleszek et al. (2013) tested Sida’s general properties for anaerobic fermentation to produce biogas and methane, and Dębowski et al. (2012) analyzed the efficiency of biogas and methane production in relation to different amounts of substrate feeding. However, because Sida contains more lignin than herbaceous plants, and because lignin hinders the decomposition of Sida biomass in the anaerobic fermentation process, breaking lignin molecules via exposing them to pretreatments is deemed a promising way to enhance Sida’s suitability as a biogas substrate. Hence, it was recommended to pretreat Sida biomass with microwaves (Zieliński et al., 2017), and Michalska et al. (2015), Michalska & Ledakowicz (2014), and Michalska et al. (2012) tested different pretreatments that facilitate the degradation of lignocellulosic biomass. When Sida was pretreated in a two-step process with sodium hydroxide and with cellulolytic enzymes, the highest biogas yields were achieved, amounting to 316 Ndm\(^3\) kg\(^{-1}\) of total solids (TS). Nevertheless, it was surpassed by Miscanthus which reached 421 Ndm\(^3\) kg\(^{-1}\) TS (Michalska et al., 2015). This amount of Sida biogas was the lowest of the studies considered, and the maximum of 470 m\(^3\) t\(^{-1}\) odm was reported by Dębowski et al. (2012). The methane content of the biogas varied between 54 % (Jablonowski et al., 2017) and 63 % (Michalska et al., 2015), and its yield amounted to between 198 Ndm\(^3\) CH\(_4\) kg\(^{-1}\) TS (Michalska et al., 2015) and 293 Ndm\(^3\) CH\(_4\) kg\(^{-1}\) organic dry matter (Dębowski et al., 2012; Hartmann & Haller, 2014). The reported differences can probably be attributed to the different methods and plant materials used in these studies. Nevertheless, Sida’s methane yield seems to be generally lower than those of maize and Miscanthus, which both typically reach amounts of more than 300 dm\(^3\) CH\(_4\) kg\(^{-1}\) dm (Herrmann & Rath, 2012; Hartmann & Haller, 2014). However, when silage made from Sida biomass was mixed with microalgal species, the amount of biogas and methane produced reached 595 and 352 mL g\(^{-1}\) volatile solids. When microalgae biomass comprised 40 and 60 % of the substrate, the highest gas yields were obtained (Dębowski et al., 2017).

Other researchers studied the biochemical composition of Sida’s cell walls in detail. The latter investigations may lead to a better understanding about which molecules are involved in the recalcitrance of Sida’s biomass, and this knowledge might in turn lead to the development of improved methods to fractionate cell wall structures in order to maximize the valorization of lignocellulosic Sida compounds for biogas production (Damm et al., 2017a,b).

Pokój et al. (2015) included Sida in their comparison of different plant species with regard to their biophysical and biochemical properties following anaerobic
digestion, and Jablonowski et al. (2017) assessed the performance of Sida used as feedstock for direct combustion and as a substrate for biogas production. The authors chose four different harvesting and processing scenarios: (i) a single harvest of Sida in January for utilization as solid fuel, (ii) a single harvest in October for biogas production, (iii) one harvest for biogas production in June followed by another harvest of regrown Sida shoots in January for solid fuel utilization, and (iv) two consecutive harvests for biogas production performed in June and October. The energy yields of these four different management scenarios calculated per hectare were 440 GJ ha\(^{-1}\) for scenario (i), 212 GJ ha\(^{-1}\) for scenario (ii), 135 GJ ha\(^{-1}\) for scenario (iv), and 85 MJ ha\(^{-1}\) for scenario (ii). Thus, using Sida as solid fuel after harvesting in winter achieved by far the highest energy recovery and its biomass fulfilled all prerequisites for the DIN EN ISO 17225-7:2014-09 norm without additional treatments after harvesting (Jablonowski et al., 2017).

Often, however, the authors of the analyses summarized in this section did not specify when exactly the Sida material analyzed was harvested, so that differences in the obtained values might also be due to different developmental stages of Sida at the biomass harvest. Hence, also in such analyses, it would be important in future to utilize the BBCH scale developed by Jablonowski et al. (2017) in order to be better able to compare the results and to assign them to a distinct developmental stage in Sida’s annual growth cycle.

The use of Sida for phytoremediation

In addition to the assessments of Sida’s biomass for energy production, Sida was tested as a means for soil quality improvement. For example, Sida has been proven to upgrade the ecological quality of a layer of sewage sludge (Borkowska & Wardzinska, 2003). The authors showed that higher densities of plants increased the uptake of Co, Fe and Ni. Plants from vegetative propagation were able to take up more Fe than plants grown from seeds. Also, Antonkiewicz et al. (2004) as well as Antonkiewicz et al. (2017) tested the ability of Sida to remove heavy metals (Cd, Cr, Cu, Ni, Zn, and Pb) from soils fertilized with municipal sewage sludge and compared it to Rosa multiflora. In both plants, increasing levels of fertilization led to increased biomass yields and heavy metal uptake. However, Sida achieved greater biomass increments and was able to take up more heavy metals than Rosa multiflora, with the exception of Pb. The ability of Sida to extract heavy metals directly from contaminated soils was first tested via pot experiments by Antonkiewicz & Jasiewicz (2002) and Antonkiewicz et al. (2006). In comparison with other plants tested such as maize, hemp (Cannabis sativa L.), amaranth (Amaranthus spp.), and Jerusalem artichoke (Helianthus tuberosus L.), Sida displayed the highest growth tolerance in response to the concentrations of heavy metals applied (Cd, Cu, Ni, Pb, and Zn) and showed particularly large accumulation potential of heavy metals in the root system (Antonkiewicz & Jasiewicz, 2002). The authors concluded that due to the high levels of metals removed from the soil, Sida may constitute a useful phytoextractor for the reclamation of chemically contaminated soils. In other experiments, Sida’s biomass yield and its ability to accumulate heavy metals were compared to Miscanthus on two different soil types (Antonkiewicz et al., 2004; Kocoń & Matykta, 2012; Kocoń & Jurga, 2017; Werle et al., 2017). In these studies, Miscanthus always produced higher biomass yields and was also superior with regard to the uptake of heavy metals from the contaminated soil. In another experiment, Sida showed a suitability to accumulate chlororganic pesticides like DDT, and thus, it proved useful for reanimations of soils contaminated with pesticides (Ignatowicz, 2015).

Other options for utilizing Sida

Apart from using Sida as feedstock for different kinds of energy production and for phytoremediation, further alternatives for its usage exist. For example, Sida can be used as raw material for the production of particle boards. Low-density particle boards of Sida biomass glued with urea-formaldehyde resins and melamine-urea-phenol-formaldehyde resins did not differ much from boards made from wood particles (Czarnecki & Dukarska, 2010). Furthermore, it can be used as a raw material for pulp and paper industries, a basic compound for natural fiber product, and as a fodder plant (Ligai & Bandyukova, 1990; Tarkowski & Truchliński, 2011). Sida’s biomass can also be used as high-quality biochar, as it contains rather low amounts of polycyclic aromatic hydrocarbons (Madej et al., 2016), and it performed better in absorbing heavy metal ions from water than commercially available biochar made from wheat straw (Bogusz et al., 2015). Sida’s suitability to limit the distribution of environmental pollutants of, for example, exhaust gases along a roadside has also been assessed. For this purpose, a greenery belt of 360 m length and 20 m width was established along a road in Poland. The greenery belt limited the distribution of heavy metals, which were allocated in the plants’ biomass, especially in the leaves, but without reaching toxic levels (Słowiak et al., 2015). Similarly, Sida has been tested as an acoustic screen along roads with excessive traffic. The maximum noise reduction of 13.4 dB was reached during the vegetation period, being significantly more intensive.
Plantation establishment

The focus of respective studies. The usage potentials of Sida as basic compound for natural fiber products and as turf substitute, they hold the potential to become important in future and should be the focus of respective studies.

The management of Sida plantations

Plantation establishment

In general, fields that are used for Sida plantations require the same seed bed preparation as used for other agricultural crops. Thereafter, Sida is recommended to be established in early May (Haller & Fritz, 2015; von Gehren & Gansberger, 2017) by sowing seeds, planting root cuttings, or planting seedlings (see also Table 1). However, owing to the risk to become infected with Sclerotinia sclerotiorum, Sida plantations should not be established on fields that were stocked with rapeseed as preceding crop (Brassica napus L.), a plant that is likely to convey the pathogenic agent (Haller & Fritz, 2015). In general, sowing seeds is the most cost-efficient method for growing Sida (Stolarski et al., 2014b). A useful amount of seeds for the plantation establishment is considered to be 1 kg ha\(^{-1}\) (Haller & Fritz, 2015). According to the determined weight of Sida seeds (Packa et al., 2014), this corresponds to about 250,000 seeds, or 25 seeds per square meter (compare also Table 1). The tiny size of Sida seeds may cause problems for automated sowing machines, but these problems can be overcome by pilling the seeds. In that case, the weight per seed is approximately doubled (Haller & Fritz, 2015). Nevertheless, deploying Sida seeds is fraught with risk because their germination rate can be unpredictably low. For example, the comparably low yields obtained on good soil by Haller & Fritz (2015) were most likely due to the low germination rate, what resulted in the thriving of weeds on the areas in which Sida seeds did not germinate well. Even in Petri dishes in the laboratory, the germination rate of untreated Sida seeds can be as low as 5–10 % on average (Kurucz & Fári, 2013). Hence, different methods to improve their germination success were tested. For example, Borkowska & Molas (2012) tested two different seed dressings to suppress fungal infections (Orius 02 WS and Sarfun T 65 TS). In both cases, the biomass yield was on average increased by 2\( \text{tdm ha}^{-1} \) during three years of growth. Techniques to break seed dormancy were also applied, such as hot water and scarification with 95% sulfuric acid pretreatments. These techniques were first tested by Borkowska & Styk (2006), and later authors followed their approach (Kurucz & Fári, 2013; Kurucz et al., 2014; Packa et al., 2014). In a comparison of different dormancy breaking methods including the two just mentioned approaches, however, mechanical scarification with a commercial pneumatic seed scarifier resulted in by far the highest germination success. With this method, seeds harvested in the same year of the scarification, but also seeds harvested one year previously, displayed a germination rate of about 90 % (von Gehren & Gansberger, 2017).

Still, freshly germinated Sida plantlets are very tiny, grow slowly in the initial phase, and can therefore easily be overgrown by weeds. In the field, this may lead to low numbers of successfully growing Sida plants that in addition require cost- and time-intensive care, because potentially applicable herbicides are likely to affect also Sida plants (Borkowska & Molas, 2008; Haller & Fritz, 2015). These problems could be overcome using alternative ways of propagation and establishment such as using seedlings and root cuttings (e.g., Borkowska & Molas, 2013; Tworkowski et al., 2014). The latter approach is nevertheless regarded critical by some authors because of its unknown virological, phytopathological, and pest-related implications (Kurucz & Fári, 2013). At present, the most commonly used approach to establish Sida plantations is planting seedlings that are commercially available in European countries such as Poland, Hungary, and Germany. These seedlings are already 10–20 cm high and thus have lead over potentially competing weeds. Yet, further research to improve the usage of pretreated seeds as described above is clearly desirable to render the plantation establishment more cost-efficient.

Plantation management and harvest

Once the Sida plants are growing, they typically require weed control, but only in the first years, until they are large enough to darken out potentially competitive weeds (Haller & Fritz, 2015). From autumn on, after the Sida shoots have shed their leaves, the water content in the shoots decreases, and from December onwards, it is low enough to harvest and store the biomass without controlling the weeds.
problems (Stolarski et al., 2014a). Nonetheless, Sida is typically harvested from January until March. It can even be harvested in April, but the harvest should definitely be performed before the new shoots start thriving (Borkowska et al., 2006a). A harvest of the biomass grown in the year of establishment is economically not viable, and mulching can be an alternative (Haller & Fritz, 2015). Sida shoots can be harvested and chipped with conventional harvesting equipment as it is used for harvesting maize (Haller & Fritz, 2015).

In comparison with SRC, Sida biomass combines several advantages regarding its harvest. For example, Sida can be harvested every year, and ubiquitously available machinery such as forage harvesters can be used. This implies that the harvest can be performed flexibly when the weather conditions are suitable, and it will typically be cheaper than SRC harvests, which need to be performed with more expensive specialized machines that are often only available at brief and defined time intervals within their harvesting course through a certain region, and that may involve additional transport costs (Nahm et al., 2012; Vanbeveren et al., 2015). Moreover, in contrast to SRC wood chips, Sida biomass is dry enough for storage and direct combustion (Stolarski et al., 2014a; Jablonowski et al., 2017), whilst SRC chips need to be dried either artificially, again involving extra costs and energy expenses, or naturally, what may involve a considerable loss of biomass because of biological degradation processes (Whittaker et al., 2016). Yet, a disadvantage of Sida and other energy plants with a comparably low biomass density such as Miscanthus spp. relates to storing the material: It requires a lot of space, what in addition implies increased costs. To cope with this disadvantage, Sida raw biomass could be converted into pellets or briquettes, as discussed above.

Economic aspects of Sida cultivation

A recent attempt to evaluate the cultivation of Sida economically, supposing the production of biomass chips, was performed by Polish researchers for a plantation established in 2009 (Stolarski et al., 2014b). They calculated the monetary gain of six different establishment approaches, based on production costs for 1 t Sida chips, and loco plantation prices for two years (2010–2011). The approaches chosen consisted of sowing seeds in amounts of 1.5 and 4.5 kg ha⁻¹, and in planting both root cuttings and seedlings in densities of 20,000 and 60,000 ha⁻¹. The production costs for 1 t Sida chips were lowest for the plot on which 1.5 kg seeds were sown (ca. 33 € t⁻¹), and highest on the plot where 60,000 seedlings were planted per hectare (ca. 50 € t⁻¹). Similarly, the biomass yield varied between 12.3 and 16 t ha⁻¹ of fresh matter with these two plots representing the extremes. The highest direct surplus was achieved on the plot on which 4.5 kg seeds were sown on one hectare (ca. 425 € ha⁻¹). When it was assumed that the Sida biomass was transported to an incineration plant in 50 km distance (what represents an inadvisable scenario), the direct surplus was reduced to about 270 € ha⁻¹. In any case, at least at this early stage of the plantation management, the higher biomass yield achieved after planting 60,000 seedlings or root cuttings was not sufficient to reclaim the increased establishment and production costs of these variants to outcompete the variant using seeds.

Conclusions

Reviewing the scientific literature about Sida, it is apparent that this plant has attracted the interest of an increasing number of research groups who recognized the potentials of Sida as raw material for different utilization pathways. Most frequently, studies examined Sida’s suitability as regenerative feedstock for bioenergy production. Indeed, given the necessity to replace fossil fuels by renewable energy sources, and to advance sustainable and ecologically improved agricultural practices in Central Europe to countersteer further biodiversity losses, it can be expected that the interest in Sida and other perennials such as cup plant will increase further, as they combine high biomass productivity with ecologically valuable effects such as soil protection and providing pollinator food.

At present, however, different research gaps need to be addressed before it can be expected that Sida will be grown on larger scales in Central Europe. First, given that Sida is a neophyte in Europe, its competitive and invasive potential needs to be assessed. Until today, not much is known about these aspects of Sida. Due to the low germination rates of its seeds, and the low competitive potential of the freshly germinated seedlings, problems regarding its potential invasiveness are generally deemed unlikely. Still, neophytes may adapt to their new environment in previously unpredictable ways. Hence, detailed investigations regarding the competitive and invasive potential of Sida are required. Second, the research reviewed in this article illustrates that especially the establishment strategies of Sida plantations could be optimized and made more cost-efficient and that its biomass productivity depends on soil and climate characteristics. Hence, more research on successful plantation establishment using pretreated seeds is desirable, as well as assessing the optimal growth conditions of Sida under different edaphic and climatic conditions. Furthermore, the susceptibility of Sida to pathogens such as S. sclerotiorum should be examined, and measures to countersteer potential infestations as
exemplified by Remleń-Starosta et al. (2016) need to be developed. Moreover, extensive economic calculations regarding the costs and revenues in full management cycles are lacking, particularly in comparison with SRC, cup plant, and Miscanthus spp. Should farmers be able to grow Sida successfully, reliable business marketing strategies and value chains need to be established. For the time being, it would clearly help if existing knowledge about Sida would be bundled and made publicly available, ideally via an online platform that facilitates the exchange of experiences between scientists, practitioners, and interested farmers.

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