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Energy crop (*Sida hermaphrodita*) fertilization using digestate under marginal soil conditions: A dose-response experiment

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Abstract

The global demand for energy security and the mitigation of climate change are the main drivers pushing the production of crops for energy purposes (energy crops). However, the cultivation of these plants can cause land use conflicts since agricultural soil is mostly used for food crop production. A sustainable alternative to the conventional cultivation of food-based energy-crops is the cultivation of non-food energy crops on marginal lands. To further increase the sustainability of energy crop cultivation systems the dependency on synthetic fertilizers needs to be reduced via closed nutrient loops in the production chain for bioenergy.

In the present study *Sida hermaphrodita* was used to evaluate its potential as an energy crop to be grown on a marginal sandy soil in combination with a fertilization using digestate from biogas production. With this dose-response experiment we identified an optimum digestate dose of 40t ha^{-1} corresponding to the highest biomass production, which was compared to an equivalent dose of mineral NPK-fertilizer. Further, 240t ha^{-1} had lethal effects on *Sida hermaphrodita*. A digestate dose of 5t ha^{-1} showed no fertilization effect. Digestate fertilization built up a pool of soil organic matter (SOM). The slow release of nitrogen from this organic pool could serve as long term fertilization and help to limit the high risk of leaching on marginal soils. Accordingly we see a potential of biogas digestate as a sustainable alternative to mineral fertilizers for the cultivation of the energy crop *Sida hermaphrodita* on marginal soils.

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Keywords: energy crops; marginal land; digestate; dose-response; *Sida hermaphrodita.*

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1. Introduction

As stated in the FAO report 2009, the competition for arable land by food and energy crops can negatively affect food security [1]. Therefore, alternatives for energy crop production on agricultural soils must be evaluated to avoid land-use and fuel versus food conflicts. A sustainable alternative is the use of degraded and marginal areas which are currently not in use or are not feasible for agricultural production. Most marginal soils are rocky, sandy or shallow with a limited reservoir of plant available nutrients and water [2]. The European Environmental Agency (EEA) defines marginal land as low quality land of whose production barely covers its cultivation costs. However, the ecological value of marginal lands is still under discussion, as they are natural habitats for many species.

Conventional energy crops such as maize are not able to grow well under such conditions. Alternatives, such as the high yielding perennial energy crop *Sida hermaphrodita* possess the ability to grow in sandy or rocky soils with low organic matter content and produce relatively high biomass yields at relatively low nutrient levels [3]. To further increase the sustainability of an energy crop production system on marginal soils, a closed nutrient cycle is required. During harvesting nutrients are removed with the plant biomass from the field. After fermentation in a biogas reactor nutrients are still present in the biogas-digestate. In our approach we used digestate from anaerobic digestion of maize silage to evaluate its potential as a fertilizer on marginal substrates. To date maize still represents the most prominent plant for biogas production. In 2012 in Germany 512,000Ha were cultivated with maize [FAOSTAT 2014]. Due to a governmental cut of subsidies for biogas plants in Germany using maize as a substrate, alternative plant materials must be found. Assuming a conversion from maize production towards a cultivation of *Sida hermaphrodita* we used maize digestate mimicking this conversion step in terms of nutrient recycling. According to Möller et al. [4] plant biomass digestates contain all nutrients remaining in the plant tissue that were absorbed from the soil during the vegetation period. Many studies already investigated the effect of digestate as potential fertilizer, and economic and ecological analyses were conducted to evaluate the value of digestate for a bio-based economy, which tries to reduce its dependency on mineral fertilizers [5]. Even after the anaerobic digestion of the biomass, digestate still contains organic components which have a positive influence on soil fertility and soil quality by serving as soil amendment [6]. It positively affects the total organic carbon content and accordingly the soil structure and texture associated with the plant-available water holding capacity [7]. Besides these effects the organically bound nitrogen in the digestate might help to minimize leaching-losses on soils with a low water holding capacity (WHC) [8]. Especially on marginal substrates leaching is of high risk [9]. Besides the positive effects of digestate on soil quality and plant growth, also negative impacts on plant growth have been reported, as high doses of digestate may cause plant mortality [10].

In the present study we want to identify an optimum digestate dose for the cultivation of *Sida hermaphrodita* on a sandy substrate, which delivers a high biomass and does not show toxicity effects. Therefore, a dose response experiment was conducted. Further we investigated to what extent different fertilizer doses and forms influence the root- (RMF), stem- (SMF) and leaf mass fraction (LMF), as results by Poorter et al. indicated [11].

2. Materials and Methods

A fully randomized greenhouse pot experiment was established in February at the Research Centre Jülich (location: 50.89942°N 6.39211°E). Plants were grown with a light period of 16h per day (natural day light in combination with an automated light system with sodium-vapour lamps [SON-T AGRO 400, Phillips] ensuring a minimum irradiance of 400µmol s^{-1} m^2), day/night temperature of 22/ 17°C and a constant humidity of 60%. Pots (11cm*11cm*12cm) were filled with a sandy substrate obtained from an open sand pit (particle size: 0-1mm; pH_{H2O} 6.6; water holding capacity (WHC): 24%; no detectable amounts of plant nutrients), which was used as a model substrate for a marginal soil. *Sida hermaphrodita* seedlings with two fully developed leaves (BBCH-stage 12) were individually transplanted into the pots. Two days after transplanting the following fertilizer treatments were applied: 1. untreated control, 2. biogas-digestate from anaerobic digestion of maize silage (provided by ADRW Naturpower GmbH & Co. Kg; N: 0.53%; P: 0.14%, K: 0.68%; organic matter: 5.3% in fresh weight) of 2.5g pot^{-1}, 5g pot^{-1}, 10g pot^{-1}, 20g pot^{-1}, 40g pot^{-1}, 80g pot^{-1}, 120g pot^{-1} ;equivalent doses to 5t ha^{-1}, 10t ha^{-1}, 20t ha^{-1}, 40t ha^{-1}, 80t ha^{-1}, 160t ha^{-1} and 240t ha^{-1} digestate field application, 3. mineral NPK fertilizer (Scotts Australia PTY Ltd; N: 15%, P: 4.5%;

K: 24.1%) of N-equivalent amounts of digestate doses of 20t ha^{-1}, 40t ha^{-1} and 80t ha^{-1}. Prior to the application to the pots, each fertilizer dose was brought into a 200ml suspension in deionized water. Each treatment was applied with five replications. To minimize the effects of nutrient leaching, fertilization was split into three applications in two weeks intervals with an exponential increase, following the approach of Ingestad [12].

Plants were grown for 41 days after the first fertilizer application and pots were kept moist at around 60% WHC via automated watering twice a day. To minimize the effect of spatial environmental variation, all pots were re-randomized twice during the experimental period. During the experiment, weekly measurements of leaf greenness were taken (SPAD-502 Konika-Minolta Marunouchi Japan), the BBCH stage of *Sida hermaphrodita* plants was determined and the height of the plants was measured [13].

At the termination of the experiment, 41 days after start of the treatments, plants were cut at ground level, roots were separated from the substrate by washing manually. Leaves stems and roots were separated and dried at 70°C until constant weight for dry mass determination. Additionally, soil samples were taken and dried to constant weight at 30°C. C and N content of the soil was determined by element analysis (VarioELcube, Elementar). Statistical analysis was performed using an analysis of variance (ANOVA $p<0.05$) of $\log_{10}$ transformed data in R 3.0.3 [The R Foundation for Statistical Computing 2014].

3. Results and Discussion

The data of the shoot dry mass presented in figure 1 (a) indicated that digestate application had a clear effect on plant biomass production. At an equivalent digestate application dose of ≥ 10t ha^{-1}, a significant increase of shoot drymass compared to the untreated control was observed. The highest biomass of the digestate variants was observed at 40t ha^{-1} and 160t ha^{-1} treatments. However, a digestate application dose of 240t ha^{-1} did not have a significant fertilization effect on shoot drymass compared to the untreated control. This may indicate possible toxicity effects of the used digestate as described by Albuquerque et al. for other species [10]. The NPK-fertilized plants produced the highest shoot drymass, however, this effect was not significant compared to plants fertilized with equivalent amounts of digestate. Mineral NPK fertilization equivalent to a digestate application of 80t ha^{-1} produced the highest shoot dry mass yielding 16 times the shoot biomass of unfertilized plants. The dose response curve for the digestate variants follows the dose response approach of Liebig and has its maximum between a digestate application of 40t ha^{-1} and 160t ha^{-1} (figure 1b) [14].

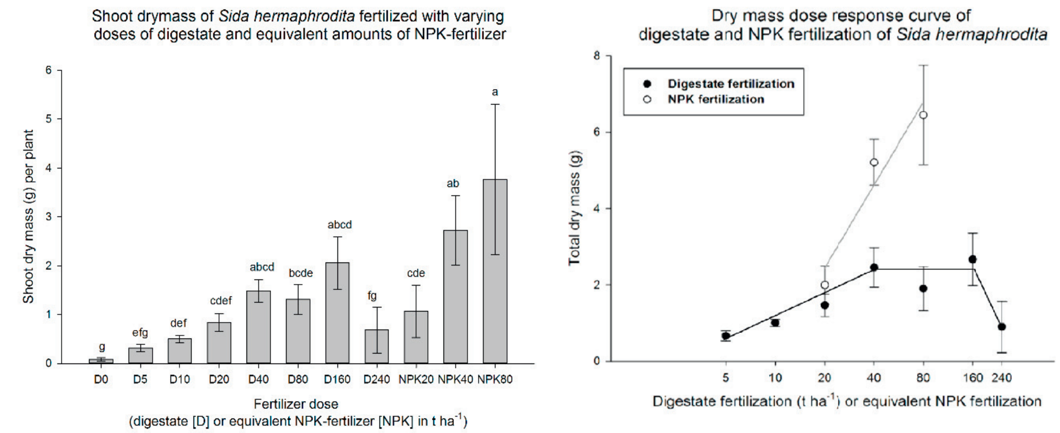

Fig 1. (a) Total shoot drymass of 41 day old *Sida hermaphrodita* plants fertilized with digestate or equivalent amounts of NPK-fertilizer; bars indicate the standard deviation of the mean (n=5); variants with the same letter are not significantly different (0.05 level); D0: untreated control; D5–D240: digestate doses of 5–240t ha^{-1}; NPK 20–80: equivalent amount of NPK fertilizer corresponding to the digestate doses of 20–80t ha^{-1}, calculated on the basis of the N-content of digestate. (b) Total drymass of 41 day old *Sida hermaphrodita* plants fertilized with digestate and equivalent N amounts of NPK-fertilizer; bars indicate the standard deviation of the mean (n=5), dose-response line follows the approach of Liebig [14].

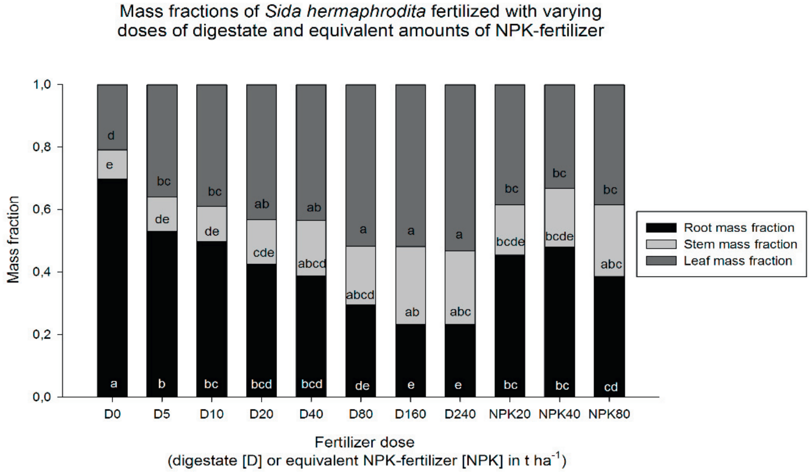

Fig 2. Root-, stem- and leaf mass fraction of 41 day old *Sida hermaphrodita* fertilized with digestate or equivalent amounts of NPK-fertilizer (n=5); variants with the same letter are not significantly different (0.05 level); D0: untreated control; D5–D240: digestate doses of 5–240t ha^{-1}; NPK 20–80: equivalent amount of NPK fertilizer corresponding to the digestate doses of 20–80t ha^{-1}, calculated on the basis of the N-content of digestate.

For the NPK fertilizer applied in equivalent doses to 20t ha^{-1}, 40t ha^{-1} and 80t ha^{-1} digestate application this maximum was not reached yet, indicating that *Sida hermaphrodita* can handle higher doses of NPK fertilization than digestate fertilization. Higher applications of the digestate did not result in significantly higher biomass yields, but increased the risk of harmful effects which delayed plant development or even caused the loss of plants.

Control plants not exposed to any fertilization had the highest observed root mass fraction (Fig. 2). The lowest dose of digestate (5t ha^{-1}) significantly reduced the root mass fraction and increased the leaf mass fraction. Low doses of digestates, as well as untreated plants expressed a higher root growth to access a larger pool of nutrients as described by Marschner et al (1996) [15]. Digestate doses equivalent to 80t ha^{-1} and higher resulted in the smallest root mass and the highest leaf mass fractions. For NPK fertilized plants the different doses did not show any significant changes in the different biomass fractions and were not significantly different to plants fertilized with equivalent amounts of digestate.

Table 1. Development Stages (BBCH-scale) of *Sida hermaphrodita* fertilized with digestate and equivalent amounts of NPK-fertilizer, means of n=5, D0: untreated control; D5–D240: digestate doses of 5–240t ha^{-1}; NPK 20–80: equivalent amount of NPK fertilizer corresponding to the digestate doses of 20–80t ha^{-1}, calculated on the basis of the N-content of digestate.

Dose	Day 1	Day 8	Day 15	Day 22	Day 29	Day 36	Day 41
D0	12	12	12	12	12	13	14
D5	12	12	13	13	14	15	16
D10	12	12	13	14	14	15	17
D20	12	12	13	14	15	15	19
D40	12	12	13	14	15	18	28
D80	12	12	13	14	15	18	22
D160	12	12	14	15	20	25	27
D240	12	12	13	13	14	15	20
NPK20	12	12	13	14	15	21	22
NPK40	12	12	14	15	20	26	29
NPK80	12	12	13	21	25	29	41

10-19: leave development | 20-29: side shoot development | 40-50: flowering

Control plants developed more slowly than fertilized plants and reached on average BBCH stage 14, by developing only two additional leaves during the experimental period of 41 days (Table 1). Digestate doses from 5t ha^{-1} to 20t ha^{-1} promoted leaf development. Higher doses of digestate promoted side shoot development during the last two weeks of the experiment. For the NPK-fertilized plants all variants showed side shoot development and the highest dose of NPK-fertilizer (equivalent to digestate application of 80t ha^{-1}) promoted side shoot formation after four weeks and promoted flowering of *Sida hermaphrodita* plants after six weeks.

Results of the soil analysis at the end of the experiment showed no detectable amounts of N for the control treatment. The small amount of C found in the soil samples of the control plants can be explained by formation of root biomass and residues from the substrates *Sida hermaphrodita* seedlings were pre-cultivated in. Clear differences of soil N and C between digestate and NPK fertilization where detected (Fig. 3). In the NPK fertilized variants detectable amounts of N and C were found with insignificant differences between the different NPK-treatments. It can be hypothesized that the amounts of C can also be explained by the formation of root biomass present in the soil sample. The detected N and C quantities in the digestate fertilized variants were proportional to the applied digestate doses. Values for the application of 40t ha^{-1} and 80t ha^{-1} were significantly higher compared to the equivalent NPK fertilized variants. The high C content in the soil indicates that N could still be organically bound and not plant available [16]. These results may also explain why NPK variants yielded higher shoot drymass than equivalent digestate fertilized variants. We hypothesize that in a longer experimental time mineralization will release organically bound N. Subsequently, this released N is likely to become available for the plants and compensate for the reduced N availability in the first weeks after the digestate application. This hypothesis is supported by previous findings described by Galvez et al [17]. Soil analysis showed that plants fertilized with mineral NPK already took up most of the N which was highly plant available compared to the N present in the digestate.

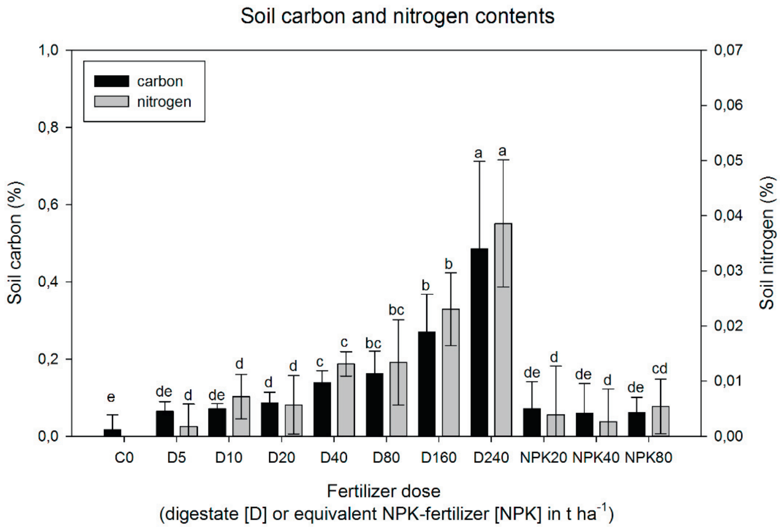

Fig 3. Soil nitrogen (N) and carbon (C) after 41 days of *Sida hermaphrodita* cultivation fertilized with digestate or equivalent amounts of NPK-fertilizer; bars indicate the standard deviation of the mean (n=5); bars with the same letter are not significantly different; D0: untreated control; D5–D240: digestate doses of 5–240t ha^{-1}; NPK 20–80: equivalent amount of NPK fertilizer corresponding to the digestate doses of 20–80t ha^{-1}, calculated on the basis of the N-content of digestate.

4. Conclusion

The presented results show a clear fertilization effect of maize digestates on *Sida hermaphrodita*, growing on a marginal sandy substrate, with an optimal application dose of 40t ha^{-1}. The nitrogen of the digestate was not directly completely plant available. This explained a reduced growth in the first weeks, compared to plants fertilized with highly soluble NPK-fertilizer. However, there was a build-up of a soil nitrogen pool providing a longer lasting N reservoir for the plants. As leaching is a high risk on marginal soils with a low WHC the organically bound nitrogen seems a promising way to reduce the loss of nitrogen.

Carefully adjusted digestate fertilization is of importance as the dose response curve showed that high doses of digestate resulted in harmful effects on young plants and caused delayed plant development with less formation of leaves, side-shoots or flowers.

These findings provide basic information on the plant *Sida hermaphrodita* grown on a sandy substrate considered as a marginal soil fertilized with digestate and will further be used for long-term experiments.

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References

[1] FAO. The State of Food Insecurity in the World Economic crises – impacts and lessons learned; 2009.
[2] Schröder P. Bioenergy to save the world. Producing novel energy plants for growth on abandoned land. Environ. Sci. Pollut. Res. Int. 2008; 15:196-204.
[3] Borkowska H, Wardzinska K. Some Effects of *Sida hermaphrodita* R. Cultivation on Sewage Sludge. Polish J. Environ. Stud. 2003;12: 119-122.
[4] Möller K, Müller T. Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. Eng. Life Sci. 2012;12: 242-257.
[5] Vaneeckhaute C. Closing the nutrient cycle by using bio-digestion waste derivatives as synthetic fertilizer substitutes: A field experiment. Biomass and Bioenergy 2013;55:175-189.
[6] Walsh JJ, Jones DL, Edwards-Jones G, Williams AP. Replacing inorganic fertilizer with anaerobic digestate may maintain agricultural productivity at less environmental cost. J. Plant Nutr. Soil Sci. 2012;175:840-845.
[7] Reeves DW. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res. 1997;43:131-167.
[8] Haraldsen TK, Andersen U, Krogstad T, Sørheim R. Liquid digestate from anaerobic treatment of source-separated household waste as fertilizer to barley. Waste Manag. Res. 2011;29:1271-76.
[9] Di H, Cameron K. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. Nutr. Cycl. Agroecosystems 2002; 237-256.
[10] Alburquerque JA, de la Fuente C, Bernal MP. Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils. Agric. Ecosyst. Environ. 2012;160: 15-22.
[11] Poorter H. Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. New Phytol. 2012;193:30-50.
[12] Ingestad T. Relative addition rate and external concentration; driving variables used in plant nutrition research. Plant. Cell Environ. 1982; 443-453.
[13] Hack H, Bleiholder H, Buhr L, Meier U, Schock-Fricke U, Weber E, Witzenberger A. Einheitliche Codierung der phänologischen Entwicklungsstadien mono- und dikotyler Pflanzen – Erweiterte BBCH-Skala, Allgemein..Nachrichtenbl. Deut. Pflanzenschutzd. 1992;44: 265-270.
[14] Liebig JV. Die Grundsätze der Agriculturchemie mit Rücksicht auf die in England angestellten Untersuchungen. Friedrich Vieweg & Sohn, Braunschweig, Ger.; 1855.
[15] Marschner H, Kirkby E, Cakmak I. Effect of mineral nutritional status on shoot-root partitioning of photoassimilates and cycling of mineral nutrients. J. Exp. Bot. 1996;47(Spec No):1255–63.
[16] Alburquerque JA, de la Fuente C, Bernal MP. Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils. Agric. Ecosyst. Environ. 2012;160:15-22.
[17] Galvez A. Short term effects of bioenergy by-products on soil C and N dynamics, nutrient availability and biochemical properties. Agric. Ecosyst. Environ. 2012;160:3-14.