Europ. J. Agronomy 87 (2017) 8–18

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Radiation use efficiency, chemical composition, and methane yield of biogas crops under rainfed and irrigated conditions

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ARTICLE INFO

Article history:
Received 30 August 2016
Received in revised form 3 March 2017
Accepted 8 March 2017

Keywords:
Bioenergy
Biogas
Drought stress
PAR interception

ABSTRACT

For biomethane production, the cup plant (*Silphium perfoliatum* L.) is considered a promising alternative substrate to silage maize (*Zea mays* L.) due to its high biomass potential and associated ecological and environmental benefits. It has also been suggested to grow cup plant on less productive soils because of its presumed drought tolerance, but robust information on the impact of water shortage on biomass growth and substrate quality of cup plant is rare. Therefore, this study assesses the effects of soil water availability on the chemical composition and specific methane yield (SMY) of cup plant. Furthermore above-ground dry matter yield (DMY) was analysed as a function of intercepted photosynthetic active radiation (PAR) and radiation use efficiency (RUE). Data were collected in a two-year field experiment under rainfed and irrigated conditions with cup plant, maize, and lucerne-grass (*Medicago sativa* L., *Festuca pratensis* Huds., *Phleum pratense* L.). The cup plant revealed a slight decrease of −6% in the SMY in response to water shortage (less than 50% of plant available water capacity). The average SMY of cup plant [306 l (kg volatile solids (VS))$^{-1}$] was lower than that of maize [362 l (kg VS)$^{-1}$] and lucerne-grass [334 l (kg VS)$^{-1}$]. The mean drought-related reduction of the methane hectare yield (MHY) was significantly greater for cup plant (−40%) than for maize (−17%) and lucerne-grass (−13%). The DMY reduction in rainfed cup plant was mainly attributed to a more severe decrease in RUE (−29%) than for maize (−16%) and lucerne-grass (−12%). Under water stress, the mean cup plant RUE (1.3 g MJ^{-1}) was significantly lower than that of maize (2.9 g MJ^{-1}) and lucerne-grass (1.4 g MJ^{-1}). Compared to RUE, the reduced PAR interception was less meaningful for DMY in rainfed crops. Hence, the cup plant is not suitable for growing on drought prone lands due to its high water demand required to produce reasonably high MHYs.

1. Introduction

Among a variety of crops used for biomethane production in Germany, silage maize (*Zea mays* L.) attains the highest MHY (Weiland, 2010). Besides the favourable chemical composition, this superiority mainly results from a high biomass yield (Amon et al., 2007a; Brauer-Siebrecht et al., 2016). Consequently, maize became the key substrate for biomethane production in Germany (DMK, 2013) and is increasingly cultivated in short crop rotations or monoculture, with the resulting negative effects on biodiversity (Gardiner et al., 2010) and plant health (Meissle et al., 2010).

In the search for alternative biogas substrates, the perennial cup plant (*Silphium perfoliatum* L.) is gaining increasing attention due to its high biomass potential (Gansberger et al., 2015) and ecological benefits in comparison to continuously grown maize (Sanderson and Adler, 2008). Furthermore, some authors expect this C3 crop to be drought tolerant (Sontheimer, 2007; Bauböck et al., 2014; Franzaring et al., 2014, 2015).

Abbreviations: ADL, acid detergent lignin; AWC, available water content; DMY, above-ground dry matter yield; $DMY_{irrigated}$, above-ground dry matter yield in irrigated plots; $DMY_{rainfed}$, above-ground dry matter yield in rainfed plots; GAI, green area index; IPAR, cumulative intercepted photosynthetically active radiation; $IPAR_{irrigated}$, cumulative intercepted photosynthetically active radiation in irrigated plots; $IPAR_{rainfed}$, cumulative intercepted photosynthetically active radiation in rainfed plots; K_{PAR}, extinction coefficient for photosynthetically active radiation; L_{IPAR}, above-ground dry matter yield-loss due to reduced cumulative intercepted photosynthetically active radiation; L_{RUE}, above-ground dry matter yield-loss due to reduced cumulative radiation use efficiency; MHY, methane hectare yield; NFE, nitrogen-free extract; PAR, photosynthetically active radiation; Q_i, transmitted radiation; Q_0, incident radiation; RUE, radiation use efficiency; $RUE_{irrigated}$, radiation use efficiency in irrigated plots; $RUE_{rainfed}$, radiation use efficiency in rainfed plots; SMY, specific methane yield; VS, volatile solids; WUE, water use efficiency.

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http://dx.doi.org/10.1016/j.eja.2017.03.001
1161-0301/

The ecologically and economically sustainable biogas production depends on choosing the most suitable crops for the available sites. In this context, knowledge of the crop specific water use patterns is essential, because drought stress is one of the most important yield-limiting factors of crop production. Drought stress has been shown to alter the chemical composition, i.e. increased fibre and decreased nitrogen-free extract (NFE) content in maize (Meibaum et al., 2012), whereas no significant effect of drought stress on chemical composition in lucerne (*Medicago sativa* L.) was found (Testa et al., 2011). Several studies have been focussing on the cup plant's SMY (Dandikas et al., 2014; Mast et al., 2014; Haag et al., 2015), DMY (Gansberger et al., 2015) and MHY (Stolzenburg and Monkos, 2012; Mast et al., 2014; Haag et al., 2015) under a wide range of growing conditions. However, none of these studies provided detailed information on the impact of drought stress on the respective target traits of the cup plant. The SMY of cup plant is considerably lower than that of maize (Dandikas et al., 2014; Mast et al., 2014; Haag et al., 2015). Therefore, the economic methane production with cup plant is mainly achieved via a high DMY.

Model calculations for various bioenergy cropping systems have shown that a high DMY essentially depends on an efficient use of the crop growth resources water and incident solar radiation (Wienforth, 2011). With respect to water use efficiency (WUE), the cup plant is regarded to be far less efficient than maize. However, its higher soil water extraction ability compensated partly for this deficiency (Schoo et al., 2016). The interception of PAR by the cup plant and the photosynthetic transformation of intercepted radiation into biomass, expressed by the RUE (Monteith and Moss, 1977), have not yet been studied. In principle a higher crop DMY can be achieved with increased and extended radiation interception and high RUE (Loomis and Amthor, 1999; Wienforth, 2011). The amount of PAR interception is determined by the crop's leaf area development (Bonhomme, 2000). Under drought stress, leaf area reduction, leaf senescence as well as wilting and rolling of leaves will reduce the amount of PAR interception, whereas decreased leaf photosynthetic rates reduce RUE (Sinclair and Muchow, 1999). Contrary to annual crops, perennial cup plant exhibits an earlier development of PAR absorbing leaf area right from the beginning of the vegetation cycle. On the other hand, the RUE of C3 plants is lower than that of C4 plants (Sinclair and Muchow, 1999). If the cup plant is actually drought tolerant, it should be able to maintain a relatively high PAR interception and RUE even under water deficit conditions.

The present study addresses the determination of the energy potential of the cup plant and its suitability as an alternative substrate for biogas production with respect to the use of water and radiation. The analyses covered the impact of drought stress on the substrate quality as well as the radiation interception and radiation use efficiency. Maize and lucerne-grass were used as reference crops.

2. Materials and methods

2.1. Field experiment

The field experiment was conducted in 2013 and 2014 at the experimental field (52.296°N, 10.438°E, altitude 76 m) of the Julius Kühn Institute for Crop and Soil Science in Braunschweig, Germany. The soil was classified as a Haplic Luvisol (FAO, 1997) with locally occurring clay rich bandings typical of a Lamellic Luvisol (FAO, 1997). The plant available soil water content at field capacity amounted to 185 mm in the upper 150 cm. The experimental plots (6 m × 40 m) were established in 2012 in a two-factorial split-plot design with four replications. In the subplots, perennial cup plant, semi-perennial lucerne-grass (*Medicago sativa* L., *Festuca pratensis* Huds., *Phleum pratense* L.) and a maize monoculture were grown under rainfed and irrigated conditions (main plots). Supplemental overhead or drip irrigation was provided for maintaining 50–80% of the plant available water content (AWC). Details on crop management are provided in Table 1.

Table 1
Details of cultural practices in the years 2013 and 2014.

	Cup plant	Maize	Lucerne-grass
Cultivars[1]	Population of Russian origin	Atletas (ripening group: late)	COUNTRY 2056 (80% *Medicago sativa* L., 15% *Festuca pratensis* Huds., and 5% *Phleum pratense* L.)
Sowing date	Crop established May 9, 2012 already	April 26, 2013 and April 16, 2014	Crop established March 21, 2012 already
Plant spacing or seeding rate	12 rows; 0.5 m between and within rows (4 plants m^{-2})	8 rows; 0.75 m between rows (9 plants m^{-2})	Four tracks with a 1.5 m seed drill at a seeding rate of 20 kg ha^{-1}
Harvest dates	August 20 (rainfed) and August 29 (irrigated) in 2013; August 6 (rainfed) and August 14 (irrigated) in 2014	October 1, 2013 and September 29, 2014	Four cuttings on May 14, June 24, August 1, and September 17 in 2013; 5 cuttings on April 28, June 14, July 15, August 18, and October 6 in 2014
Harvested area	160 m^2 (8 central rows)	120 m^2 (4 central rows)	120 m^2 (two central seed drill tracks)
Irrigation[2]	2013: 215 mm (11); 2014: 230 mm (11)	2013: 235 mm (12); 2014: 120 mm (6)	2013: 235 mm (12); 2014: 120 mm (6)
Basic fertilisation (kg nutrient ha^{-1} yr^{-1})	41, 237, 33, 39 of P, K, Mg, S in 2013 and 30, 199, 61, and 76 of P, K, Mg, and S in 2014	41, 237, 33, 39 of P, K, Mg, S in 2013 and 40, 252, 61, and 74 of P, K, Mg, and S in 2014	41, 270, 36, and 43 of P, K, Mg, and S in 2013 and 30, 274, 30, and 33 of P, K, Mg, and S in 2014
Nitrogen fertiliser (kg N ha^{-1} yr^{-1})	170	180	30
Application date	March 3, 2013 and March 10, 2014	May 3, 2013 and April 30, 2014	March 27, 2013 and March 10, 2014
Form	Uniformly calcium ammonium nitrate		
Weed control[3]	None	Tank mix with 100 g ha^{-1} mesotrione, 43.2 g ha^{-1} nicosulfuron, and 15 g ha^{-1} prosulfuron	Side effect of multiple cutting
Pest and disease control[3]	Tank mix with 650 g ha^{-1} boscalid and 100 g ha^{-1} pyraclostrobin against grey mould (*Botrytis cinerea*) at June 4 and 6, 2013 and May 5 and 15, 2014	100 g ha^{-1} pirimicarb at July 7, 2013 against aphids	None

[1] Seedlings of the cup plant were purchased from N.L. Chrestensen, Erfurt. Seeds of maize and lucerne-grass were kindly provided by the KWS Saat AG and the Deutsche Saatveredelung AG (DSV), respectively.
[2] Number of irrigation events in brackets. Overhead and drip irrigation were applied.
[3] Amount of active ingredients.