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BIOGAS PRODUCTION FROM CATCH CROPS: A SUSTAINABLE AGRICULTURAL STRATEGY TO INCREASE BIOMASS YIELD BY CO-HARVEST OF CATCH CROPS AND STRAW.

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ABSTRACT: Catch crop cultivation combined with its use for biogas production would increase renewable energy production in the form of methane, without interfering with the production of food and fodder crops. The low biomass yield of catch crops is the main limiting factor for using these crops as co-substrate in manure-based biogas plants and the profit obtained from the sale of biogas barely compensates for the harvest costs. A new agricultural strategy to harvest catch crops together with the residual straw of the main crop was investigated to increase the biomass and thereby the methane yield per hectare. Seven catch crops harvested together with the stubble of the main crop (spring wheat) were evaluated. The effects of stubble height and harvest time for different catch crops/straw blends were studied. Biomass yields were up to 3.6 t of TS ha⁻¹ of which the catch crop constituted around 10% of the total biomass. Leaving the straw on the field until harvest of the catch crop in the autumn could benefit biogas production due to the organic matter degradation of the straw taking place on the field during the autumn months. This new agricultural strategy may be a good alternative to achieve economically feasible biogas production from catch crops and straw.

Keywords: Biogas, crop, agricultural residues, straw.

1 INTRODUCTION

Catch crops are used in agriculture mainly to reduce nutrient losses in soil. They are grown after the main crop, retaining nutrients from the soil and releasing them during the following growth season. In this way, they reduce the need for fertilizer and contribute to protect the aquatic environment. Based on this contribution of catch crops to the sustainability in the cultivation of food and fodder crops, the mandatory cultivation of catch crops on farms larger than 10 hectares [1], and the increasing implementation of centralised biogas plants for treating up to 40% of the total manure until 2020, catch crops have become of major interest as a source of agricultural biomass for manure-based biogas production in Denmark.

The feasibility of using catch crop biomass as a co-substrate for manure-based biogas plants in Denmark has been recently studied [2, 3]. The volume of methane that can be obtained per hectare of crop (m³ ha⁻¹), which is the product of the biomass yield (t of volatile solids (VS) per hectare) and the specific methane yield of the catch crop (m³ t⁻¹ of VS), is the main parameter determining the economic viability of using catch crops as substrate for anaerobic digestion [4]. In general, catch crops provided biomass yields between 1 and 3 t of total solids (TS) per hectare [3]. The biomass yield of a catch crop depends on several parameters such as time of establishment, time of harvest and fertilisation. An earlier establishment favoured generally higher biomass yields. A later harvest may lead to higher biomass yields; however, the biodegradability of more mature biomass can be reduced due to the lignification of the plant. Fertilisation may also improve biomass yields by up to 77% but the effect of fertilisation on biomass yield varies considerably depending on soil type, climate conditions and the ability of the crop to uptake nutrients [5]. Specific methane yields for catch crops in the range of 229-474 m³ t⁻¹ of VS have been reported for catch crops [3]. Since growth time of the crop, climate conditions and nutrient availability are influencing the development of the plant, and thus the chemical composition of the biomass, these

parameters also determine the specific methane yield [6][7][8]. Furthermore, the specific methane yield is correlated to the specific catch crop specie. In this way, the highest methane yields were found to correspond to the catch crop species belonging to Brassicaceae and Graminaceae botanical families. On the contrary, crops like *Cannabis* sp., *Helianthus* sp., *Lupinus* sp. or *Phaseolus* sp. presented generally lower methane yields [3]. In total, the volume of biogas that can be achieved per hectare of catch crop was rather determined by the biomass yield of catch crop per hectare than by the specific methane yield of the catch crop biomass. Therefore, increasing the biomass yield would determine the economic feasibility of using catch crops for biogas production [2].

The objective of the present study was to evaluate a new agricultural strategy with the aim of increasing the biomass yield of catch crops. In this manner, the catch crops were harvested together with the stubble left of the main crop (spring wheat). The biomass and specific methane yields of seven catch crops, in the mixture with the stubble were evaluated. The effect of stubble height on biomass yield and specific methane yield was studied. The effect of harvest time on the chemical composition, biomass yield and specific methane yield of the stubble of spring wheat was also assessed.

2 MATERIAL AND METHODS

2.1 Agricultural practices and sampling: Trial 1 – catch crop species and species mixtures.

Trial 1 was carried out to study biomass yield and specific methane yield from the harvest of different catch crops together with stubble from the previous main crop. Spring wheat was sown on April 10th 2013, using a seed rate of 240 kg ha⁻¹, and the catch crops were sown on April 10th 2013 (T1-T3) and July 5th 2013 (T4-T7). The following catch crops or crop mixtures were cultivated (Table 1): Perennial ryegrass and white clover (*Lolium perenne* and *Trifolium repens*; T1), fescue (*Festuca* sp.; T2), red clover (*Trifolium pratense*; T3), oil seed radish

(*Raphanus sativus* var. *oleiformis*; T4), oil seed radish with N fertilization (T5), oil seed radish and winter vetch (*Vicia sativa*; T6) and oil seed radish and red clover (T7). The trial was designed as a randomized block design with four replicate blocks and a plot size of 13.5 m².

In the area with trial 1, weeds were controlled by spraying with herbicide. Diseases and insects were controlled chemically, using a conventional control strategy. The whole field was sprayed with growth regulator to reduce the straw length of the spring wheat in order to avoid lodging. The spring wheat was harvested on August 29th 2013 by an experimental cereal harvest machine, adjusted to a stubble height of approx. 45 cm above soil level. The crop height of the spring wheat was approx. 80 cm, and the 'upper fraction' of the straw which was harvested was left on top of the stubble. On September 6th 2013, 50 kg of N ha⁻¹ was applied to the catch crop in treatment T5. The catch crops were harvested together with stubble from the previous main crop on October 31st, 2013, using an experimental forage harvest machine.

A representative biomass sample was taken from each plot for analysis of the specific methane yield. All samples of approx. 1 kg were frozen at -18 °C directly after harvest until methane yield analysis. Biomass yields were calculated as t of total solids (TS) per hectare and t of VS per hectare.

Table I: Biomass yields, total and volatile solids and methane yields for freshly harvested biomass from trial 1. C: only straw; T1-T7: mixtures of straw and different catch crop species

Straw/ catch crop sample	Stubble height cm	Biomass yield t of TS ha ⁻¹	Total solids %	Volatile solids % VS of TS	Biomass yield t of VS ha ⁻¹	Methane ^a yield m ³ t ⁻¹ of VS	Methane yield per hectare m ³ ha ⁻¹
<i>Trial 1</i>							
C	45	3.2	36.8	92.8	3.0	159	470
T1	45	3.6	37.5	93.3	3.3	172	576
T2	45	3.3	31.9	94.3	3.2	239	754
T3	45	3.4	41.4	95.9	3.3	195	643
T4	45	3.2	38.4	91.4	3.0	180	533
T5	45	3.4	30.5	95.8	3.2	177	571
T6	45	3.5	39.9	96.3	3.4	186	626
T7	45	3.3	40.3	95.6	3.2	165	523

^aSpecific methane yield after 57 days of anaerobic digestion.

2.2 Agricultural practices and sampling: Trial 2 – stubble height and harvest time

Trial 2 comprised the evaluation of stubble height on biomass yield and specific methane yield as well as the effect of harvest time on the composition and specific methane yield of spring wheat stubble (Table 2). Trial 2 was located adjacent to trial 1 in the same field with spring wheat. In the whole area, spring wheat cv. Amaretto was sown on April 10th 2013 by conventional machinery, using a seed rate of 240 kg ha⁻¹. On April 20th 2013, a catch crop was sown, using a seed rate of 20 kg ha⁻¹ of perennial ryegrass (*Lolium perenne*). The area for trial 2 was treated as mentioned for trial 1 in terms of fertilization and control of weeds and pests, except that weeds were controlled by spraying with different herbicides.

The trial was established on August 24th 2013, when the spring wheat was harvested. Two samples were

harvested with different stubble height using a conventional harvest machine. The stubble height was set at approx. 40 cm (sample 2A) or 55 cm (sample 2B), harvesting a distance of 30 m with each height. This was done in three replicate blocks according to a Latin square design with three harvests and three replicate blocks and a gross plot size of approx. 250 m².

In order to study the biomass yield and methane potential of pure stubble from spring wheat over time, a sub-plot of approx. 50 m (6×8.5 m) within each of the three plots with 40 cm stubble height was sprayed with glyphosate on September 6th 2013 to kill the perennial ryegrass catch crop. On September 6th (sample 2D) and September 27th (sample 2E), stubble yield was measured manually in 1 and 2 m² net plots, respectively, and on October 31st 2013 (sample 2F) stubble yield was measured by harvesting 13.5 m² with an experimental forage harvest machine. On all three dates, stubble samples were taken for analysis of methane potential, and samples were dried at 50°C and stored as dry biomass until the analysis.

On October 31st 2013, biomass yield was measured in all 9 plots by harvesting the catch crops together with the stubble of various heights, using an experimental forage harvest machine. The forage harvester with a width of 1.5 m was harvesting perpendicularly to the harvest direction of the cereal harvester, representing a cross section of the working width of the cereal harvester (approx. 8.5 m) including the two tracks where the stubble had been run down by the wheels. Consequently, the net plot size was approx. 13.5 m². For the plots with 40 cm stubble height, yield was both measured in the part of the plot with catch crop (treatment 2A) and in the part of the plot where the catch crop was killed by glyphosate (treatment 2F).

Table II: Biomass yields, total and volatile solids and methane yields for freshly harvested biomass from trial 2. 2A, 2B: mixtures of straw and Perennial ryegrass; 2C, 2D, 2E: only straw at different harvest times.

Harvest sample	Stubble height cm	Biomass yield t of TS ha ⁻¹	Total solids %	Volatile solids % VS of TS	Biomass yield t of VS ha ⁻¹	Methane ^a yield m ³ t ⁻¹ of VS	Methane yield per hectare m ³ ha ⁻¹
2A	40	3.2	42.7	95.6	3.0	171	518
2B	55	3.2	44.0	96.6	3.1	205	628
2D	40	3.4	84.3	96.4	3.3	143	475
2E	40	2.7	66.9	97.3	2.6	172	443
2F	40	2.8	57.3	96.2	2.7	203	551

^aSpecific methane yield after 57 days of anaerobic digestion.

2.3 Methane yield determination

Methane yield was determined in batch experiments according to the methodology followed by Biswas et al. [9]. Anaerobic sludge was used as inoculum at mesophilic conditions. The inoculum was taken from an anaerobic lab-scale digester treating swine manure. TS and VS of the inoculum were 36.39 ± 0.20 g L⁻¹ and 20.41 ± 0.40 g L⁻¹. Batch vials (117 cm³ total volume) were filled with 30 mL of inoculum and approximately 1 g volatile solids (VS) of biomass sample. Batch tests were performed in triplicates. Blanks containing 30 mL of inoculum were set-up in triplicate to determine the endogenous methane production of the anaerobic inoculum. The vials were gas tight sealed with a rubber stopper and a metal clamp and flushed with a mixture gas of 80% N₂ and 20% CO₂ in order to ensure anaerobic

conditions. The vials were incubated at $37 \pm 2^\circ\text{C}$. Methane production was monitored by measuring the methane concentration in the headspace using gas chromatography [9]. Methane production was measured until no more gas production was observed.

2.4. Chemical analyses

Biomass samples were analysed for TS and VS according to APHA [10]. The content of carbohydrates and lignin was determined by the strong acid hydrolysis-Klason lignin method, based on the NREL analytical procedures [11].

Biogas composition was analysed using a gas chromatograph (SRI GC model 310), equipped with a Porapak Q column of 182.88 cm length and 2.1 mm i.d. Nitrogen was used as carrier gas with a pressure of 196 kPa. The injector and detector temperatures were 80°C ; the temperature of the oven was constant on 80°C . The retention time for methane with these parameters was about 0.4 min. As standard gas, a mixture of 30% CH_4 and 70% N_2 was utilised.

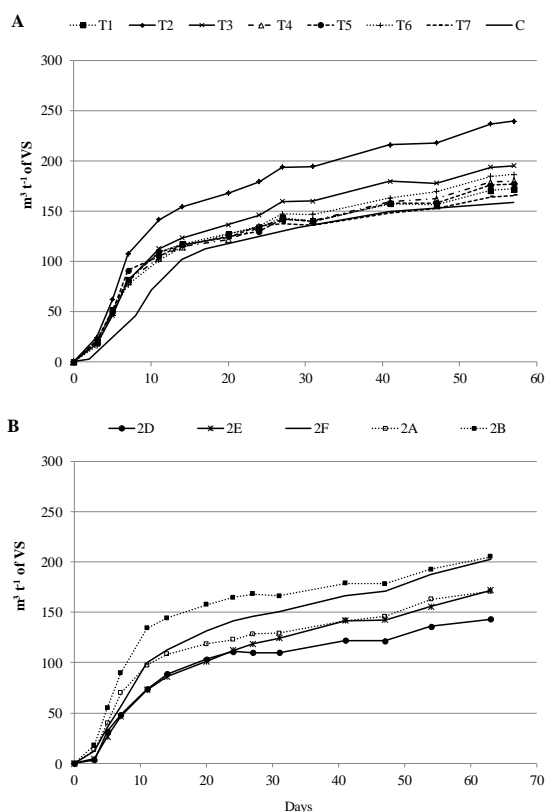


Figure 1: Accumulated specific methane yield in trial 1 (A) and trial 2 (B).

3 RESULTS AND DISCUSSION

3.1 Trial 1: Biomass yield and specific methane yield from catch crops together with stubble.

Biomass yields in the range of 3.3 and 3.6 t of total solids (TS) per hectare were obtained for the different combinations of catch crop and stubble (Table 1). Catch crops contributed in the range of 3-10% to those yields. The highest contribution of the catch crops (0.4 t of TS ha^{-1}) was observed for the blend of perennial ryegrass and white clover (T1), sown in April. The catch crops sown on April 10th did not have significantly higher yields than

catch crops sown on July 5th, so the time of establishment did not appear to be the limiting factor for the catch crop yield. Therefore, the relatively low contribution from catch crops to the total biomass yield was probably due to the dry summer and the lack of available nitrogen, which may have limited the growth of the catch crops.

Accumulated methane yields for the different catch crops and stubble blends are presented in Figure 1A. Specific methane yields after 57 days of anaerobic digestion were in the range of 165-239 $\text{m}^3 \text{ t}^{-1}$ of VS (Table 1). As it was expected, all of the catch crop and stubble blends (T1-T7) presented higher methane yield than the straw alone (C; 159 $\text{m}^3 \text{ t}^{-1}$ of VS). The combination of fescue and stubble (T2) achieved the highest methane yield of 239 $\text{m}^3 \text{ t}^{-1}$ of VS, representing a 51% increase if compared to straw alone (C). Specific methane yields for the catch crop and stubble blends were, on the other hand, up to 2.9 times lower than for catch crops alone as obtained in previous studies [3]. The lower methane yields in the mixture of catch crops and stubble can be attributed to the high lignin content of the stubble (Figure 2).

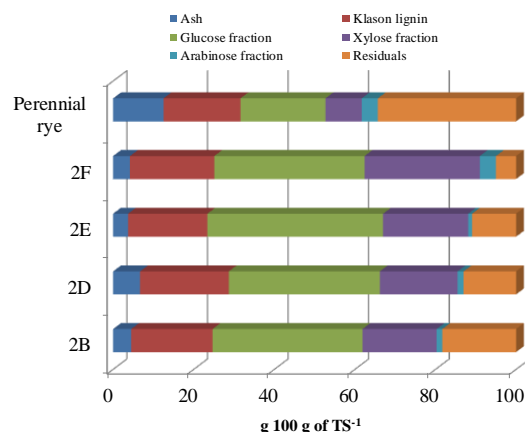


Figure 2: Chemical composition of fresh biomass of spring wheat stubble (2D, 2E, and 2F), stubble blend (2B) and a pure catch crop (Perennial ryegrass, obtained from previous experiments)

The calculated methane yields per hectare of catch crop and stubble blend was in the range of 523-754 m^3 per hectare. These values were generally higher than those values obtained for catch crops alone (78-812 m^3 of methane per hectare) [2]. Figures 3 and 4 present the production price per cubic meter of methane in relation to the biomass yield depending on the harvest costs, dry matter concentration (TS) and the methane yield of the crop. These production costs were estimated after different scenarios both for pure catch crops (Figure 3), based on the data reported by Molinuevo-Salces et al. [3], and blends of catch crop and wheat stubble (Figure 4), based on the data from the present study. No additional costs were accounted for the establishment of the catch crops, since catch crops are currently mandatory to cultivate on 10-14% of the Danish farmland [1]. Moreover, no additional costs were accounted for transferring the digested slurry from the biogas plant back to the field where catch crops were harvested. The calculations were based on the current revenue for biogas production in Denmark, which is 0.154 EUR kWh^{-1} .

In addition to the pronounced effect of biomass yield, the reduction of the harvest costs from 200 to 134 EUR

ha⁻¹ shows to have the main impact on reducing the overall production costs. The analysis shows that for the higher harvest costs, biomass yields above 1.3 and 2.5 t of TS per hectare are needed to obtain an economic feasible production of biogas from catch crops and from the blend of catch crops and stubble, respectively. On the other hand, biomass yields around 1-1.5 t of TS per hectare would be sufficient to pay back the production of biogas from catch crops and catch crop blends in the case of harvest costs of 134 EUR ha⁻¹.

The lower biodegradability and thereby lower specific methane yield of the wheat straw in the blends is counteracted by the effect of the higher biomass yield and the greater total solids content with higher VS/TS proportion of the stubble and catch crop blends, if compared to catch crops alone (Table 1, Figures 3 and 4). In this way, the methane volume threshold for a feasible biogas production process would be in the same range in the case of the blends and catch crops alone. More specifically, in the case of catch crops, with an average VS/TS ratio of 83% and an average specific methane yield of 345 m³ t⁻¹ of VS, a threshold of 1 t of TS ha⁻¹ would be equivalent to a methane yield of 287 m³ ha⁻¹. For the blends of catch crops and wheat stubble, with an average VS/TS ratio of 95% and a specific methane yield of 188 m³ t⁻¹ of VS, a threshold of 1.5 t of TS ha⁻¹ would be equivalent to a methane yield of 268 m³ ha⁻¹.

The methane yields per hectare achieved by this agricultural approach were above the estimated threshold for all the different blends (Table 1). Therefore, this new strategy may be a good alternative for economically feasible biogas production from catch crops and stubble from the main crop for biogas production.

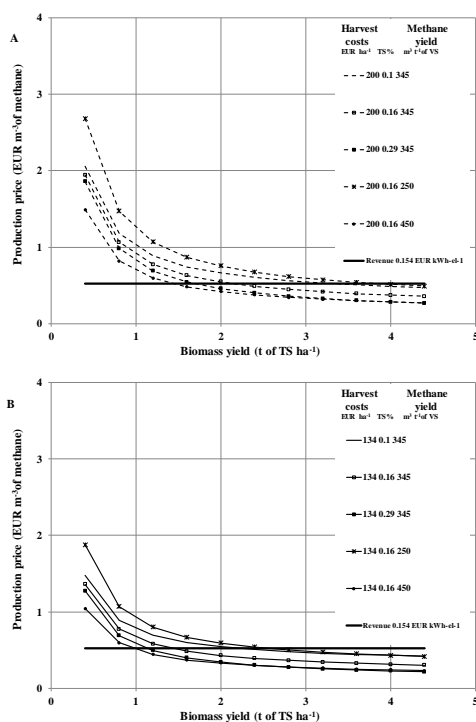


Figure 3: Production costs versus biomass yield under different scenarios for catch crops, for harvest cost of 200 EUR ha⁻¹ (A) and 134 EUR ha⁻¹ (B)

3.2 Trial 2: Effect of harvest time on composition and specific methane yield of wheat straw stubble.

The effect of stubble height on biomass yield and specific methane yield was studied by harvesting spring wheat at two different stubble heights (55 and 40 cm, 2A and 2B, respectively) and then harvest the stubble together with the catch crop, perennial ryegrass in this case. Whereas no difference in biomass yield was detected, the specific methane yield was 1.2 times higher for the longer stubble height (Table 2). This latter difference in methane yield could probably just be a consequence of a sampling error due to the heterogeneity of the samples.

The effects of harvest time on the chemical composition and the methane yield of the wheat stubble were studied in treatments 2D, 2E and 2F. These treatments corresponded to harvest times of 13, 44 and 78 days after harvest of the spring wheat, respectively. While biomass yields were slightly declining for the later harvest times although not statistically significant, the specific methane yield increased as the wheat straw stayed longer on the field (Table 2, Figure 1B).

No change in lignocellulosic composition with time was observed (Figure 2), but the higher methane yield achieved by the crops that stayed longer on the fields could indicate organic matter degradation, most probably carried out by the hydrolytic activity of the microorganisms upon the straw. In this way, the bioavailability of the lignocellulosic structures could have been increased, resulting in higher methane conversion but not affecting the overall chemical composition of the biomass.

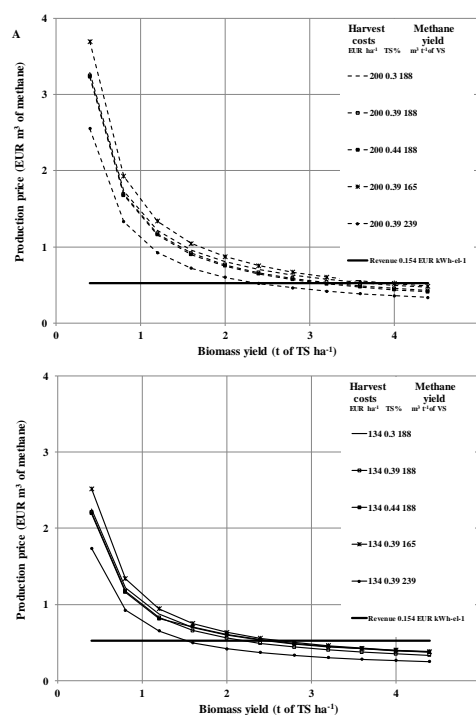


Figure 4: Production costs versus biomass yield under different scenarios for catch crops and stubble from spring wheat, for harvest cost of 200 EUR ha⁻¹ (A) and 134 EUR ha⁻¹ (B).

4 CONCLUSIONS

Harvesting catch crops together with the stubble from the previous main crop resulted in biomass yields in the range of 3.2-3.6 t of TS ha⁻¹, where the catch crop

represented around 10% of the total biomass yield. For the catch crop/straw mixtures methane yields per hectare of 523-754 m³ ha⁻¹ could be achieved, being significantly higher than the threshold for an economically feasible yield of 268 m³ ha⁻¹. The actual yield is strongly influenced by climate conditions, soil quality and harvest, transportation, handling and storage costs of crops. Late harvest of straw/stubble could benefit methane production since hydrolytic microorganisms from the soil may partially degrade the organic matter, resulting in higher methane specific yields.

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