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Lignocellulosic biomass feeding in biogas pathway: state of the art and plant layouts

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Abstract

The traditional pathway for biogas production consists in the anaerobic digestion of starchy and sugar biomass mainly from dedicated energy crops, needing agricultural land and heavy irrigation. A retrofitting of the existing biogas plants is proposed in order to reduce competition with food crops and to increase the sustainability of the whole chain in terms of land and water consumption; moreover the use of the lignocellulosic biomass is evaluated. The biomass after physical, chemical or biological pretreatment can be digested in a biogas plant to reduce the current diet without affecting the biogas production.
The present study analyzes the state of the art in the lignocellulosic biomass feeding into biogas plants and describes a preliminary techno-economical study of the pathway and the layout to be adopted, including the efficiencies and energy yields of the involved processes.

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Keywords: Biogas, lignocellulosic biomass, pretreatment, steam explosion, energy flow, supply cost, plant retrofitting.

Nomenclature

HMF	5-hydroxymethylfurfural
VS	volatile substance
C/N	carbon/nitrogen ratio
WW	wet weight
DM	dry matter

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1. Introduction

Lignocellulosic resources are very abundant, avoid competition with food agriculture and reduce feedstock costs since they can be obtained from agricultural and forestry residues, or from energy crops (cardoon, miscanthus, switchgrass) in marginal lands. This biomass was recently studied for second generation bioethanol production for transport sector [1,2]; another interesting pathway is anaerobic digestion for biogas production in co-digestion with traditional substrates (maize, sorghum and manure).

Anaerobic digestion is a biological process carried out by a consortium of microbes that produce biogas with methane percentage between 50% and 80%. The process flow (Figure 1) begins with hydrolysis, where bacteria reduce complex polymers (carbohydrates, proteins and fats) to simple molecules (amino acids, fatty acids and sugars); follows fermentation where simples molecules are converted into short chain volatile fatty acids, acetogenesis, where the last products are converted mainly into acetate, and metanogenesis for the final methane conversion [3].

In order to allow the possibility to use this kind of biomass in anaerobic digestion, one or more pretreatment steps are necessary in order to deconstruct biomass and facilitate microbes access to cellulose and hemicellulose.

The steam explosion is one of the most interesting pretreatment, where biomass is heated at high pressure with steam and then brought back at atmospheric pressure causing an explosive decompression that cause the disruption of the biomass fibers.

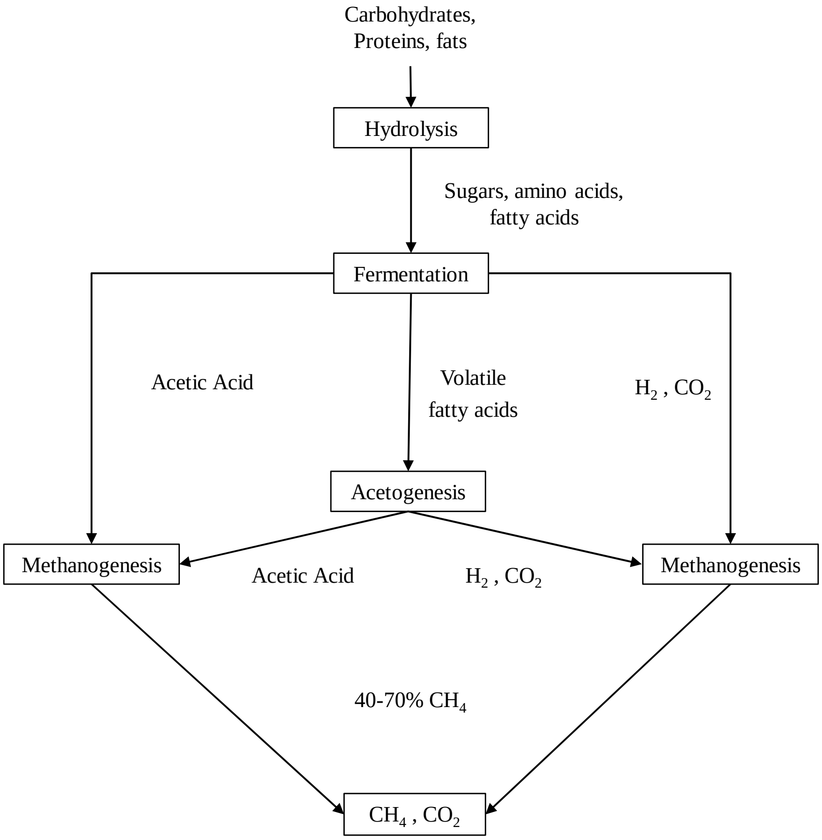

Fig. 1. anaerobic digestion process flow.

The steam explosion process is described by severity factor ($\log R_0$) expressed in function of the temperature and the duration of the pretreatment [5].

In previous works different biomass were tested in a steam explosion reactor [6-7]. The quality of biomass deconstruction increased with the pretreatment severity, however increased also the formation of toxic compounds and inhibitors such as furfural, 5-hydroxymethylfurfural (HMF), formic acid, levulinic acid, acetic acid, phenolic compounds [8].

The microbes involved in the anaerobic digestion process seems to be more tolerant to inhibitors compared to microorganisms involved in the ethanol production, excluding phenolic compounds that decreased biogas production [4].

2. Biogas potential from lignocellulosic biomass

Recent studies tested the methane potential of different typologies of lignocellulosic biomass pretreated with steam explosion; some works experimented the biomass-to-biomethane pathway, while others experimented an integrated pathway producing both ethanol (from raw material) and methane (from the distillation residue).

Birch was steam exploded with severity factor between 3.1 and 5.0, and then subjected to enzymatic hydrolysis before anaerobic digestion (37°C and 46 days); best results were obtained at 4.5 severity factor, evidencing that high severities reduced methane efficiency due to the modifications of lignin and formation of pseudo-lignin. The highest methane production was 369 l methane per kg volatile substance (VS). The study observed that a part of pseudo-lignin (syringaldehyde, furfural and HMF) was also converted into methane [8].

In another study wheat straw was steam exploded at different temperatures (160°-200°C) and residence times (10-20 min), following anaerobic digestion; the highest methane production was 331 l methane per kg VS at the most severe conditions, while the untreated biomass obtained 275.6 l methane per kg VS. The best results is only 20% higher than untreated raw material, remarking the low impact of pretreatment in this kind of biomass [9].

Corn stover, wheat straw, yard waste and leaves were investigated through enzymatic hydrolysis and solid state anaerobic digestion, without any pretreatment. Highest methane results were 66.9 l methane per kg VS for wheat straw, 81.2 l per kg VS for corn stover, 55.4 l per kg VS for leaves and 40.8 l per kg VS; each result is lower than other literature data probably due to high total solid content during anaerobic digestion [10]. Another study, even if reached better results, confirmed the low potential of anaerobic digestion of untreated lignocellulosic biomass: after 30 days anaerobic digestion both corn stover and wheat straw produced approximately 130 l methane per kg VS biomass, while maple and pine obtained only around 50 l methane per kg VS biomass [11].

Salix was steam exploded at temperatures between 170°C and 230°C and residence times between 5 and 15 min, followed by anaerobic digestion (37°C for 57 days); best yield was 240 l methane per kg biomass [12].

Alternative sources are lignocellulosic wastes (sugar beet pulp and spent hops), that are subjected to enzymatic hydrolysis before anaerobic digestion, that improve methane production [13].

Corn stover was investigated for ethanol production, while methane potential (from washing liquid after steam pretreatment and thin stillage after distillation) was evaluated as a secondary process; best yield obtained was 127 l methane per kg raw material [14].

The most efficient way to produce biogas from lignocellulosic material seems to be the recovery of liquid fraction after biomass pretreatment (steam explosion and enzymatic hydrolysis) for bioethanol production, that maximize energy recovery, since also inhibitors and lignin polymers could be digested and transformed into methane.

Also lignocellulosic residues from agriculture (corn stover, wheat straw) could be used for anaerobic digestion, after steam explosion pretreatment that in some cases produces low benefits; when using biomass with high lignin content from forestry and agriculture (birch, salix, pine, prunings), steam explosion is necessary and may be followed by enzymatic hydrolysis before anaerobic digestion, in order to remove a part of lignin that could slow digestion and reduce methane production [15].

In the next paragraph we studied some energy flow to evaluate the lignocellulosic biomass necessary to feed biogas plants and the supply cost.

3. Methods

3.1. Definition of the scheme of the plant and input data

The retrofitting analysis of biogas plants was carried out considering a 1 MW electric powered biogas plants fed by two typical biomasses: the former plant diet is represented by 100% energy crops (corn and triticale silage); the latter diet is provided with a co-digestion of a biomass mix composed in equal part in weight by swine manure and energy crops [16].

The proposed retrofitted plant aims at reducing raw materials from energy crop and replace with byproducts feedstock such as straw mixed with wood residues and pruning, widely available from the agroforestry activities, without sensibly modify the C/N ratio requested by the biological process. The residual lignocellulosic abundance may represent an environmental resource in energy crops replacement and land safe for biomass anaerobic digestion feeding, but need to be pretreated with a steam explosion reactor coupled with the digester as represented in the following scheme (Fig. 2).

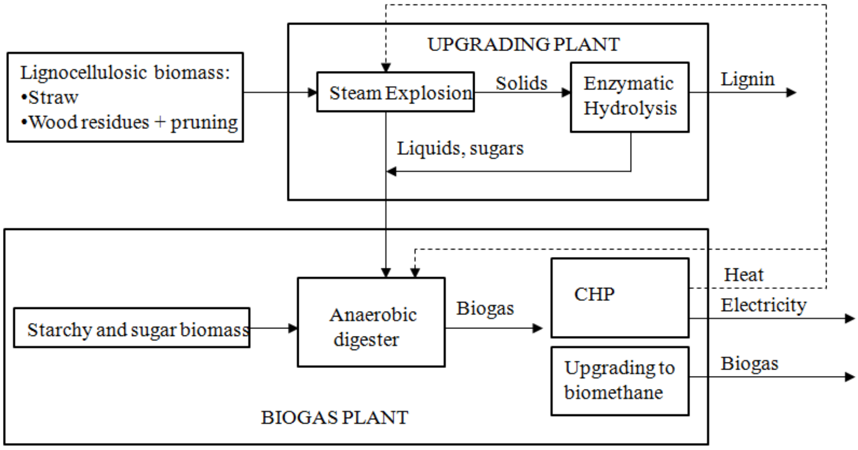

Fig. 2. anaerobic digestion process flow.

The steam explosion pretreated lignocellulosic biomass was analyzed in literature and the moisture content and the organic volatile solids were detected [17]. By assuming 65% as average content in methane, the biogas yield and raw material production cost is reported in the table below (Table 1).

The supply cost of biomass, expressed as wet weight (WW), was evaluated considering, in case of wood feedstock, an equal mix of pruning from the surrounding areas of the plant and wood residues to be collected and carried to the plant within a 50 km defined area. The transportation cost of the straw feedstock cost was evaluated considering a local production surrounding the biogas plant.

The steam explosion pre-treatment cost must be added to the biomass cost. The extra cost components are evaluated for a steam explosion treatment equipment coupled to 1 MW electric powered biogas plant and they are represented by the equipment depreciation, management (insurances, manpower) and the operating costs (water, electricity etc.). The final cost for the steam explosion biomass feedstock pretreatment are reported in the Table 2.

Table 1. Biomass feedstock physical and energy characteristics and cost.

Biomass feedstock	DM [%]	VS [% of DM]	Methane yield [Nm^3/ton VS]	Biogas yield [Nm^3/ton WW]	Cost per unit [€/ton WW]
Wood forest residues and pruning	50	95	200	150	50
Straw	85	95	300	370	60

Table 2. Steam explosion pretreatment cost by biomass feedstock.

Biomass feedstock	Depreciation [€/ton DM]	Management [€/ton DM]	Operating costs [€/ton DM]	Final cost [€/ton DM]
Wood forest residues and pruning	30	10	25	65
Straw	30	10	20	60

The operating costs for wooden biomass pretreatments are more expensive than straw due to the heavier treatment and longer retention time for steam explosion to deconstruct the more recalcitrant lignocellulosic fibers.

4. Result and discussions

The agronomic characteristics to define the land surface occupation and the cost for biomass production from energy crops are: a crop yield of about 50 t/ha and 40 €/t for corn silage; 30 t/ha and 30 €/t for triticale biomass production [18]. Based on literature data [19], the total biomass flows and the biogas yield and production were estimated; an average methane content of 65% in biogas was computed and the electric efficiency of the referred engine for biogas combustion was fixed in 37% [20]. The engine power efficiency and the methane content in biogas could be considered constant in many typical applications.

Table 3. Biomass and biogas flows, land consumption to feed 1 MW electric powered biogas plant.

Plant	Biomass feedstock	Biomass feeding [tons/year]	Land consumption [ha]	Costs [€]	Biogas production [Nm^3/year]
Plant A	Corn silage	12,200	245	490,000	2,033,000
	Triticale silage	7,400	245	220,000	1,367,000
	TOTAL	**19,600**	**490**	**710,000**	**3,400,000**
Retr. A	Corn silage	6,100	122	245,000	1,016,000
	Triticale silage	3,700	123	110,000	683,000
	Wood and residues	3,900	-	322,000	570,000
	Straw	2,900	-	322,000	1,081,000
	TOTAL	**16,600**	**245**	**999,000**	**3,350,000**

Table 4. Biomass and biogas flows, land consumption to feed 1 MW electric powered biogas plant.

Plant	Biomass feedstock	Biomass feeding [tons/year]	Land consumption [ha]	Costs [€]	Biogas production [Nm^3/year]
Plant B	Corn silage	11,000	220	441,000	1,830,000
	Triticale silage	6,600	221	199,000	1,230,000
	Swine manure	17,000	-	-	268,000
	TOTAL	**34,600**	**441**	**640,000**	**3,328,000**
Retr. B	Corn silage	5,500	110	220,000	915,000
	Triticale silage	3,300	110	99,000	529,000
	Swine manure	17,000	-	-	268,000
	Wood and residues	2,500	-	206,000	365,000
	Straw	3,400	-	377,000	1,267,000
	TOTAL	**31,700**	**220**	**902,000**	**3,344,000**

Table 5. Economic and land consumption comparison between existing and retrofitting plants.

Plants compared	Cost increasing	Land reduction
Plant A/Retr. A	40,6%	50%
Plant B/Retr. B	41,3%	50%

Table 6. Methane yield and cost per biomass typology.

Biomass	Methane yield [Nm^3/ton WW]	Methane cost [€/Nm^3]
Corn silage	166	0.37
Triticale	160	0.29
Swine manure	16	0.00
Forest residues and pruning	95	0.87 (0.71*)
Straw	242	0.46 (0.35*)

*the cost is expressed at the net of the depreciation cost of the steam explosion plant

Once the biogas production from the traditional plants was evaluated, the total lignocellulosic biomass needs to replace the 50% biomass from energy crops was estimated to guarantee the biogas flow to feed 1 MW powered engine for energy production. Table 3 shows the biomass flows characterizing the traditional biogas plants fed by 100% energy crops (Plant A) and the respective retrofitted plant replacing 50% biomass from energy crops using pretreated wooden matter and straw (Retr. A).

Table 4 synthesizes biomass and biogas flows feeding a plant by 50% energy crops, 50% animal slurry (Plant B) and the respective retrofitted plant replacing 50% biomass from energy crops using pretreated wooden matter and straw (Retr. B).

Table 5 summarizes the comparison between each basic plant and its retrofitted plant, to define the economic and land consuming ratios after the proposed application of the steam explosion pretreatment technology for lignocellulosic biomass.

The cost increasing in the proposed application based on lignocellulosic biomass is about 40% due to the fixed costs for biomass pretreatment and to the higher supply costs; the replacement of energy crops biomass with the lignocellulosic ones can reach a reduction of 50%, because the biomass supply is obtained with byproducts as straw or residues from cereal harvesting and wooden residues as pruning or forestry maintenance.

Finally, in order to compare the traditional and innovative raw materials both technically and economically, an evaluation of methane yield (Nm^3/ton WW) and methane cost has been performed. Table 6 shows the methane yield and cost in both agriculture and lignocellulosic biomass. Regarding methane production cost, forest residues and pruning have the highest cost, due to low methane potential and huge supply cost; also straw shows higher cost compared to corn silage and triticale, but the difference is reduced and becomes comparable excluding the depreciation of the extra-investment for pretreatment.

5. Conclusions

Biogas production from lignocellulosic biomass from agriculture subproducts (straw, prunings) and forestry residues was investigated, comparing methane efficiencies of these raw materials with the “traditional” biomass. Straw has interesting methane yield potential and lower pretreatment costs compared to the other lignocellulosic biomass. A techno-economic analysis of a 1 MW existing plant in two typical biomass supply configurations has been evaluated, comparing with other configurations using lignocellulosic biomass. Although the higher supply costs (+40%) for the proposed application due to the operative costs for steam explosion and the investment costs for pretreatment, there are important environmental advantages: the reduction of the land usage (50%) leads to a carbon emissions and water consumptions reduction. The higher incentives for electricity produced from the energy enhancement of lignocellulosic residues instead of food products could further reduce supply costs.

The economic suitability could be reached in a biorefinery, where lignocellulosic biomass is obtained from the residues of second generation bioethanol production (wastewater from pretreatment and fermentation residues), drastically reducing investment and supply costs. Future activities regards laboratory tests of pretreatment and biogas production from lignocellulosic substrates in order to optimize methane yield and reduce production costs.

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