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Evaluation of the biological methane potential of various feedstock for the production of biogas to supply agricultural tractors

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ABSTRACT

This work is divided into three parts. The first one presents results of biological methane potential of agriculture raw materials available in Poland. In the second part the simple mathematical model of methanogenic fermentation is proposed. The data for this model were obtained from experimental digestion process of chosen mixtures. Last part includes the results of research of exhaust emissions generated by dual dual-fuel engine of agricultural tractor powered by mixture of model biogas (60% and 70% of methane) and diesel oil. The obtained results revealed that there was a significant difference in chemical composition and yield of biogas between considered feedstock types. The highest biogas and methane production was obtained for mixtures in ratio of 6:4 for swine manure/maize silage and whey/grass silage. Due to agriculture conditions in Poland and obtain results, the maize silage and swine manure were chosen to development of mathematical model of fermentation process. It showed a satisfactory match to the experimental results.

Results of emission tests on dual-fuel tractor engine supplied with biogas and diesel oil showed the higher concentrations of hydrocarbons and carbon oxide and lower concentrations of particulate matter in exhaust gases. Level of emission of particular components depends on the biogas composition.

1. Introduction

Biogas is a gaseous product of the biological decomposition of organic matter. It is a mixture consisting of 40–75% methane (CH_4), 15–60% carbon dioxide (CO_2) and a trace amounts of other gases such as hydrogen sulphide (H_2S), ammonia (NH_3), hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), oxygen (O_2) and siloxanes [1]. More detail information about composition of biogas is included in [2]. The anaerobic digestion (AD) process consists of four main stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis [3].

The quality of produced biogas depends on type of used substrates and technology. AD process is sensitive to changes in environmental conditions due to delicate balance that occurs in this heterogenic population of microorganisms. There are many factors affecting the anaerobic fermentation process e.g.: hydrogen partial pressure, concentration of microorganisms, type of substrate, organic loading rate, hydraulic retention time, temperature, pH, C/N/P ratio [2]. During digestion it is very important to avoid substances and level of process parameters which adversely affect the AD. Detailed review of inhibitors of anaerobic digestion was presented in [4].

As substrates for the biogas production many types of biodegradable organic wastes from agriculture and industry can be used. The organic content of dry matter, the decomposition rate, bioavailability for the bacteria varies according to the substrate nature. It has direct influence on the amount of produced biogas, as it was stated in work [5], animal dung is better raw material for biogas production than kitchen wastes. Orange peel showed lowest yield of biogas because its toxic effect for process. Among raw materials from agricultural and agro-food industry, according to the authors of [6], the lowest theoretical biogas yields per 1 kg of

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Nomenclature

AD	anaerobic digestion
BMP	biochemical methane potential
CHP	combined heat and power
C/N/P	atomic ratio of carbon, nitrogen and phosphorus
C/N	atomic ratio of carbon and nitrogen
COD	chemical oxygen demand
GRETL	Gnu Regression, Econometric Time-series Library
HC	hydrocarbons
ON	Polish acronym for diesel oil (PN-EN 590)
PM	particulate matter
R^2	coefficient of determination
V_b	biogas volume
V_{CH4}	methane volume
VIF	variance inflation factor
VS	volatile solids
d.m.	dry matter content
d.m.o.	organic dry matter content
$d_{d.m.}$	difference in dry matter content before and after fermentation
$d_{d.m.o.}$	difference in organic dry matter content before and after fermentation
d_{COD}	difference in chemical oxygen demand before and after fermentation
$m_{s.m.}$	swine manure mass
s_{CH4}	methane content in biogas
t	total fermentation time

dry organic matter showed cattle slurry (200 dm^3) and the highest – sugar beet (860 dm^3). The yield of produced biogas can be increased, for instance by co-fermentation. The authors of [7], studied co-fermentation of sewage sludge and grease trap sludge from a meat-processing plant at 35 °C. They stated that methane production potential of sewage sludge alone was 278 dm^3 per 1 kg of dry organic matter. Addition of grease trap sludge resulted in significant increase in methane yield. The maximum (463 dm^3 per 1 kg of dry organic matter) was obtained for 46% of feed volatile solids of grease trap sludge). Higher content of grease trap sludge not influenced on methane yield or caused decrease in CH_4 production. It indicates that appropriate selection of substrates is important for efficiency of fermentation process.

According to the Polish Energy Law, only agricultural biogas (after upgrading) can be introduced into a gas grid. This document defines agricultural biogas as a gas produced in agricultural biogas plants, merely from agriculture and agro-food industry substrates. In Poland the most common agricultural feedstock for the AD process are manure and silages. However, the biogas production from manure is low efficient due to the low dry matter content (about 8%) [8]. Therefore, the additional substrates, such as plants with a high dry matter content are used to improve the efficiency of bioprocess by balancing carbon to nitrogen (C/N) ratio. It considerably improves the overall economics of the process. Simplified scheme of biogas production in agricultural biogas plant is presented in Fig. 1.

Biogas can be used for heat production in boilers or electrical energy generation in gas engines or special turbines. Very common option is the use of biogas in cogeneration (CHP process), for the simultaneous obtaining of usable heat and electricity [9]. In this case the only requirement to biogas quality is lack of H_2S and water vapour that are the main cause of corrosion and reduces the lifetime of the installation elements [10]. Partial removing of CO_2 from biogas can profitably influence the energy efficiency of fuel. Authors of [11] studied the effect of CH_4 content (60% and 73%) to power generation in 30 kW generator. They stated that power generation increases with higher methane concentration.

Injecting biogas into the natural gas distribution network or using it as a fuel for road vehicles, requires the additional cleaning and upgrading of biogas to natural gas quality (biomethane). For this purpose, apart from the H_2S and water vapour, the removal of trace impurities and CO_2 is required. Not all vehicles have so elevated demands regarded to the fuel properties e.g. agricultural tractors and machines but there is lack of any research concerning the use of biogas as fuel to power them.

The use of biogas in internal combustion engines has been studied by many researchers. Generally, biogas is used in dual-fuel Compression Ignition (CI) engines rather than Spark Ignition (SI) engines, in which it causes the derating of power [12]. There are numerous studies reporting the use of biogas in stationary CI engines. Those engines can be adapted to dual-fuel mode without significant changes in their construction [13]. Author of [14] studied the influence of CO_2 content in biogas on the performance of biogas/diesel dual-fuel engine (two-cylinder, four-stroke, water-cooled). He stated that the concentration of CO_2 in biogas up to 40% did not significantly deteriorate engine performance compared with the case when engine was supplied with natural gas (96% methane). Similar research was carried out by authors of [15] with the use of dual-fuel stationary engine (two-cylinder, four-stroke, water-cooled). They stated that biogas consisted of more than 37% CO_2 influenced engine run. Their study revealed that it is possible to substitute up to 60% of diesel oil by natural gas without knock.

The use of biogas to power engines has another advantage – the reduction of exhaust emissions. Authors of [16] examined exhaust gas emissions of stationary CI engine running on a mixture of biogas (95% CH_4 and 5% CO_2) and diesel oil. The research indicated that the presence of biogas resulted with a decrease of CO and hydrocarbons (HC) concentrations. However, it also caused an increase of nitrogen oxides (NO_x) concentration. Different results were obtained by [12] whose study was focused on the effect of compression ratio on the performance and emission characteristics of a dual-fuel diesel engine run on raw biogas (60% CH_4 and 40% CO_2). Their general conclusions were that, regardless of compression ratio, CO and HC emissions were larger and NO_x smaller under dual-fuel mode than under diesel mode. There is also a need for further research aimed at determining the effects of biogas used as a vehicle fuel.

In the frame of project No.: 5030E!, Acronym: BIOGASFUEL realised, among others, by the authors of this paper the dual-fuel supply system for diesel engines was developed and implemented. One of the aspects of this work was the modification of agricultural biogas production technology. It was intended to ensure the powering a tractor with a dual-fuel supply system with biogas that characteristics is as much similar to crude one as possible. In order to do this it was necessary to properly determine the methanogenic potential of the agricultural substrates mentioned above and the crude biogas composition. It was stated, based on engine tests, that the minimal methane concentration in gaseous fuel for agricultural tractor has to be above 50% v/v.