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LIFE CYCLE INVENTORY OF ANAEROBIC DIGESTION AT THE WASTEWATER TREATMENT PLANT OF A DAIRY COMPANY

Abstract: Biogas installations located on the premises of production plants are part of sustainable development policy, mainly because of their dual purpose. These plants are the ideal way to minimize various types of solid and liquid organic waste and furthermore to provide a stable source of renewable energy. Biogas produced in anaerobic digestion can be purified and injected directly to the grid, or what is more popular, subsequently combusted in a gas engine and converted into heat and power. The necessity to manage the huge amounts of effluent from milk production, mainly in the form of whey, forces dairies to constantly introduce new improvements related to wastewater treatment plants. In the investigated dairy plant, an anaerobic biogas reactor was launched, in order to improve the performance of the existing sewage plant. The main purpose of this modernization was the pollutant load reduction of dairy wastewater. The biogas made in this fermentation process was converted into thermal energy and used for heating the running biogas reactor as well as the production processes in the dairy. These studies were designed to evaluate the potential environmental impact of the anaerobic part of the upgraded wastewater treatment plant located at the dairy. The findings can be used in the decision-making process in other food processing plants where large amounts of organic wastewater are produced. In this research the Life Cycle Assessment (LCA) methodology was used. This paper presents the results of an environmental study on the second step of the LCA analysis. A Life Cycle Inventory (LCI) was used to identify the unit processes in the life-cycle of biogas production in the sewage plant at the dairy. All data were collected in a small local dairy company located in the Wielkopolska Region, Poland.

Keywords: dairy, biogas, LCI, wastewater.

JEL classification: Q29, Q42, Q54.

ŚRODOWISKOWA ANALIZA ZBIORU WEJŚĆ I WYJŚĆ PROCESU BEZTLENOWEJ FERMENTACJI W OCZYSZCZALNI ŚCIEKÓW ZAKŁADU MLECZARSKIEGO

Streszczenie: Przyzakładowe biogazownie stanowią cześć polityki zrównoważonego rozwoju, między innymi z uwagi na ich dualizm działania. Są doskonałym sposobem na minimalizację róźnego rodzaju odpadów organicznych stałych i płynnych, a także stanowią stabilne źródło energii odnawialnej. Wytworzony biogaz w procesie fermentacji beztlenowej może być po oczyszczeniu bezpośrednio wtłaczany do sieci lub kierowany na silnik gazowy i zamieniany na energię elektryczną i cieplną. Konieczność zagospodarowania olbrzymich ilości ścieków z produkcji mleka, głównie w postaci serwatki, wymusza na mleczarniach coraz to nowe ulepszenia związane z przyzakładowymi oczyszczalniami ścieków. W badanym zakładzie uruchomiono beztlenowy reaktor biogazowy w celu poprawy wydajności funkcjonującej oczyszczalni. Głównym celem takiej modernizacji była redukcja ładunku zanieczyszczeń ścieków mleczarskich. Wyprodukowany biogaz zaczęto również przekształcać w energię cieplną do ogrzania samego reaktora, jak i ogrzewania procesów produkcyjnych w mleczarni. Powyższe badania mają na celu oszacowanie potencjalnego oddziaływania na środowisko zmodernizowanej beztlenowej części oczyszczalni ścieków znajdującej się przy mleczarni. Wyniki mogą być wykorzystywane w procesach decyzyjnych innych rolno-spożywczych zakładów produkcyjnych wytwarzających duże ilości ścieków pochodzenia organicznego. W badaniu wykorzystano technikę Life Cycle Assessment (LCA). W artykule przedstawiono wyniki drugiej fazy analizy LCA. Do identyfikacji procesów jednostkowych cyklu życia produkcji biogazu w oczyszczalni ścieków w zakładzie mleczarskim wykorzystano analizę zbioru wejść i wyjść (LCI). Wszystkie dane uzyskano z małej, lokalnej mleczarni znajdującej się na terenie Wielkopolski.

Słowa kluczowe: mleczarnia, biogaz, LCI, ścieki.

Introduction

In an effort to reduce their environmental impact, agri-food industry operators need to keep up with the latest waste treatment and environmental emissions handling technologies [Chodkowska-Miszczuk and Szymańska 2013]. New technological solutions are not always a burden on the budgets of the companies which install them. On the contrary, they may produce benefits that are not only environmental but also financial. Businesses are also increasingly aware of their corporate social responsibility and of the operational efficiency gains and innovation they stand to gain from investing in environmental protection.

One of the largest segments of Poland's food sector is the dairy industry, which ranks as the country's third largest in terms of output and the fifth largest in terms of exports [Anielak 2008, p. 57]. Due to the sheer scale of its operations, the industry makes use of utilities, packages and shipping services on an enormous scale. Thus, dairy plants generate more liquid waste than any other food processing sector, largely organic. As much as 90% of the water used in the dairy industry becomes process wastewater. Plants need to dispose of it without harming the environment. The parameters of dairy plant wastewater depend on a number of factors such as production technologies as well as the products produced and the methods applied to wash and disinfect process lines [Demirel, Yenigun, and Onay 2004]. The effluent produced is mostly of organic origin. The most hazardous effluent coming out of dairy production is whey. Its degradation requires a great deal of oxygen (high biological and chemical oxygen demand: BOD and COD) [Michalska et al. 2013]. Needless to say, the wastewater is very costly and energy-intensive to treat. The perfect and innovative method of its disposal is to use in-house wastewater treatment plants relying on aerobic fermentation. Such plants are not only a way of treating wastewater but also a source of cheap and environmentally-friendly energy in the form of biogas [Igliński et al. 2012]. The dairy plant studied in the project set up an anaerobic biogas reactor in 2010. Its initial goal was to improve its existing waste-water treatment plant and burn the biogas in a torch. However, one year into the project, they combusted the biogas in a steam boiler and converted it to heat used partly in the biogas reactor and partly in the production process. The study is aimed at assessing the potential environmental impact of having upgraded the anaerobic section of the waste-water treatment plant at a dairy company and showing the environmental benefits of such installations with a view to encouraging other producers who generate biodegradable waste.

1. Material and methods

For the purposes of this paper, the study relied on data produced in a questionnaire survey conducted at the Chodzież branch of the Czarnków-based District Dairy Cooperative. The plant was selected for its production profile, the volume of organic liquid waste it generates and the method applied in its treatment. The study employed the LCA (Life Cycle Assessment) method used widely in assessing environmental impact over product life cycles [ISO 14040:2006]. The study began with the stocktaking of qualitative and quantitative data broken down by individual processes. The premise was that the study would cover the waste-water treatment plant operation "gate to gate", i.e. from the passage of the wastewater stream through a floatation column to the generation of a specified volume of biogas and its conversion into heat. The input/output stocktaking was based primarily on the original data acquired at the dairy plant. The chemical composition of the influent was ascertained with the help of the relevant literature. To identify the exact functions of the products in question, which are critical for [Lewandowska 2006], it is necessary to determine the functional unit. In this case, the selected unit was *the generation of 1MWh of heat*.

2. General description of the company waste-water treatment plant

The Chodzież plant in question is owned by the District Dairy Cooperative of Czarnków. It is fitted with state-of-the-art machinery and is 100%-Polish owned. Its core business is to produce cottage cheese and powdered milk. The average daily milk output is 800 m^3. The process generates 600 m^3 of whey per day. As whey is gradually phased out in its application as farm animal feed, the Company has taken steps to produce powdered whey. As part of the plant's continuous improvement, a new high-quality powdered milk line was completed in 2007. Despite such efforts, the treatment plant received a substantial volume of dairy waste leading to occasional capacity problems. The year 2010 marked the completion of the anaerobic segment of the treatment plant: an ASBx biogas reactor with a capacity of 1800 m^3, a floatation column, a rotary screen and a secondary sedimentation tank.

Shown below is a general diagram of the company wastewater treatment plant in Chodzież (Figure 1). Marked in red is the part of the installation examined in the study.

The "gate-to-gate" study focused on the three processes of wastewater pumping, floatation and anaerobic fermentation focusing in particular in the processes taking place in the anaerobic reactor, biogas production and its further use for heat generation in the plant. The treatment plant in question

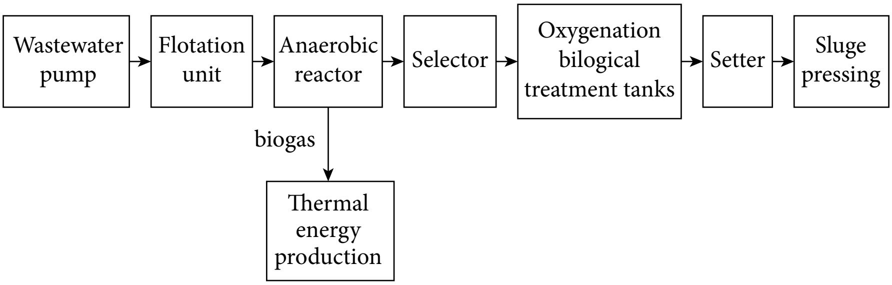

Figure 1. General diagram of the company wastewater treatment plant in Chodzież

Source: Own research based on empirical data

relies on a highly efficient Flomar® pressure floatation column. It involves the continuous treatment of effluent with integrated lamella plates for the flotation treatment of industry waste that includes preliminary flocculation. The particles generated during precipitation are immediately separated from the liquid fraction by means of a pressure floatation system. This method is used primarily for separating out fats [EnviroChemia 2015].

The influent stream is subsequently fed into an 1800 m^3 ASBx anaerobic EGSB reactor which forms a positive-pressure vertical tank. The raw influent is fed from the reactor base at a specified speed that achieves the proper momentum by means of a distribution system which efficiently responds to variations in influent characteristics. A special dual-phase separator is installed at the base of every EGSB reactor. The separator channels the biogas produced at the reactor's base producing jets of up flowing biogas and slurry. After passing a bed of active anaerobic methanogenic sludge, the jets capture granulated sludge. A mix of influent and sludge moves through a built-in triple-phase separator at the top of the reactor. To prevent losing even the smallest methanogenic sludge floccules, the triple-phase separator has been fitted with a special separation section. The anaerobic sludge slides down to where the granulate remains suspended and where the flocci in time condensate into new sludge granules. The reactor ensures maximum operational stability thanks to an automatically adjustable external recirculation system. Once treated, the effluent leaves the reactor by a sewage pipe. Meanwhile, the biogas is sent off to be burnt in a torch or used elsewhere. Shown below is the overall scheme outlining the reactor's operation (Figure 2) [Seung 2009].

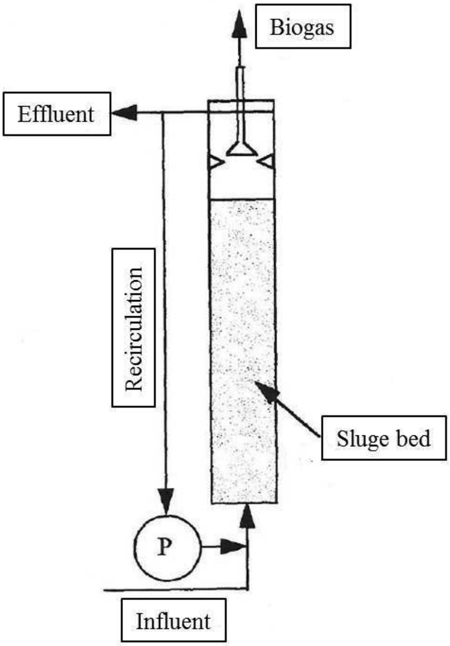

Figure 2. General operation of the ASBx anaerobic EGSB reactor

Source: [Seung 2009]

2.1. Wastewater profile

The composition of the wastewater generated in the dairy plant fluctuates on a daily and weekly basis. The wastewater is largely a mix of milk; chemical washings, process chemicals, whey and whey densification permeate. Its chemical oxygen demand is enormous ranging from 3,000 to as much as 7,000 per dm^3 of effluent. The permeate, which is a filtrate, is a thinner solution (with particles) generated by permeation through a filtration membrane [Króliczak and Jankowski 2008]. Cottage cheese production in the dairy plant generates acidic effluent. In powdered milk production, evaporators are treated with soda lye, which generates basic reaction effluent.

The plant includes a nanofiltration system for nitric acid recovery and recycling. While one should ideally be able to recover the soda lye, in the case in question, for neutralization purposes, the soda lye would have to be added directly to the nitric acid found in the wastewater before the biogas rector is installed.

There are four types of wastewater generated in the dairy industry [Michalska et al. 2013]: process water generated in cooling and heating (it is contaminant-free and may be recycled back into the system), industrial water produced by washing the installation containing whey and other milk products comprising process effluent, which in the case of the plant in question is whey, the permeate and sewage. The table below describes the composition of dairy waste generated in cottage cheese production, as derived from the literature, and average wastewater composition data based on studies conducted in the Chodzież plant downstream of flotation and methane fermentation.

Table 1. Dairy wastewater composition

Indicator	Unit	Cleaning	Cottage cheese production	Wastewater after flotation	Wastewater after reactor ASBx
pH	mgO_2/dm^3	9.6	6.6	5.9	6.7
ChZT	mgO_2/dm^3	1,200	3,420	4,014	666
BZT_5	mgO_2/dm^3	515	1,900	–	–
Oxidability	mgO_2/dm^3	290	1,020	–	–
Solid residue	mg/dm^3	nb	1,920	–	0.21

Source: Own research based on empirical data and literature [Michalska et al. 2013].

Table 2. Specifications of permeate generated in acidic whey nanofiltration

Indicator	Unit	Average value
ChZT	mgO_2/dm^3	1,990
BZT_5	mgO_2/dm^3	1,265
$N_{całk.}$	$mg\ N/dm^3$	120
$P_{całk.}$	$mg\ P/dm^3$	37.7
Dry weight	%	0.165
Proteins	%	0.05
Lactose	%	0.042
Ash	%	0.053
Fat	%	0.02
Lactic acid	%	0.04
pH	–	5.0

Source: Own research based on literature [Zieliński, Dembowski, and Krzemieniewski 2007].

The majority of the wastewater generated in the Chodzież dairy plant is acidic whey produced in cottage cheese production. Given the average milk consumption of 800 m^3 per day, the plant generates 600 m^3 of raw whey which it then passes through membrane nano-filters and crystallizes to permeate. Densified in this manner to a 50% dry mass content, the whey ends up in a drying tower whereas the permeate is channelled to the treatment plant. While the application of membrane treatment for acidic whey has attracted a great deal of interest, the permeate generated in the process is a challenge to treat. However, studies show that a properly conducted anaerobic process ensures effective treatment [Zieliński, Dembowski, and Krzemieniewski 2007]. The plant puts out approximately 450 m^3 of effluent per day. An average of 320 m^3 of wastewater which has passed preliminary treatment is fed to the reactor after flotation. Table 2 shows the permeate specifications [Zieliński, Dembowski, and Krzemieniewski 2007].

2.2. Biogas

The biogas installation at the dairy plant has been put in place primarily in response to the pressing need for reducing large contaminant contents in dairy effluent. As early as the first year in operation, the biogas the company produces turned out to be useful for process heat generation. In the first year, the installation produced 100,000 m^3 of biogas. Since a lot of time was needed to install a Loos steam boiler for biogas combustion and heat generation, one third of the gas was turned into energy. The remaining biogas was burnt in a torch. After the first year of running the ASBx reactor, the volume of highly contaminated wastewater, the acidic whey and permeate, was increased to produce more biogas. However, other process machinery constitutes a bottleneck. Due to the insufficient capacity of the blower used to feed the biogas to the boiler, once biogas production reaches ca. 700 m^3 per day, the biogas is combusted simultaneously in the torch and the steam boiler. Thanks to the use of an active bed in the reactor, the resulting biogas has the calorific value of 26.2 MJ/kg or 26.9 MJ/m^3 and the chemical composition as shown in the table below.

A constant process temperature is maintained in the reactor. Since the process is mesophilic, the temperature stands at ca. 31°C. While at the reactor's inlet the wastewater has the pH of approximately 5.1, the pH increases to 7.6 at the outlet. The hourly capacity of the recirculation pump is 90 m^3.

As of February 2014, when the data was gathered, an average of 12 m^3/h and ca. 320 m^3/day was fed into the reactor. A total of 1,500–1,800 m^3 of

Table 3. Biogas composition

Biogas composition	Quantitative composition
CH_4	73.8 %
CO_2	24.4 %
O_2	0.0 %
NH_3	outside the scope of detection
H_2S	976 ppm
H_2	81 ppm

Source: Own research based on empirical data.

biogas per day was produced, 90% of which was used to generate heat while only 10% was relegated to the torch.

Based on literature from the US Environmental Protection Agency concerning Air Pollutant Emission Factors [US EPA 2000] from burning biogas the annual emissions of gases into the atmosphere were calculated (Table 4).

Table 4. Amount of exhaust gases from burning biogas in a Loos steam boiler

Exhaust gas composition	Amount (Mg)
CO_2	1182.600
NO_x	0.946
PM10	0.112
CO	0.199

Source: Own research based on empirical data.

The plant's natural gas demand varies by season between 5,000 and 6,000 m^3/day. This means that with the methane content in the biogas amounting to 74%, the biogas satisfies roughly 30% of the plant's biogas demand. This makes the installation a whole lot more profitable while reducing the Company's environmental impact by substantially cutting the consumption of non-renewable fossil fuels.

3. Individual processes reflected in LCI research

To assess the environmental impact of a product made by what effectively has become a biogas plant, the LCI analysis should begin by defining the system's borders, i.e. the scope of the study. One should then enumerate all the individual processes and ascribe data regarding specific material and energy inputs and outputs [ISO 14044:2006]. The study encompassed the stage of wastewater pumping from the plant proper to the floatation column, the primary wastewater treatment in the floatation column, the methane fermentation in the ASBx reactor and the production of heat in the Loos steam boiler. The study has left out the stage of constructing the biogas section of the treatment plant as well as its possible demolishing and scrapping. Also left out where the stages of the aerobic section of the waste-water treatment plant – these were omitted as they could not be compared with other biogas plants, the purpose of the research being to assess the environmental impact of the biogas plant depending on the biological input rather than the environmental impact of wastewater treatment. That is why the functional unit was not selected on the basis of the volume of the waste treated but rather on the basis of the amount of energy produced per time unit. Neither has the research been extended to the movement of wastewater across processes, as such movement was gravitational. With respect to energy consumption, only the initial pumping of the wastewater from the plant to the floatation column was taken into account. Shown below is the overall LCI model diagram (Figure 3).

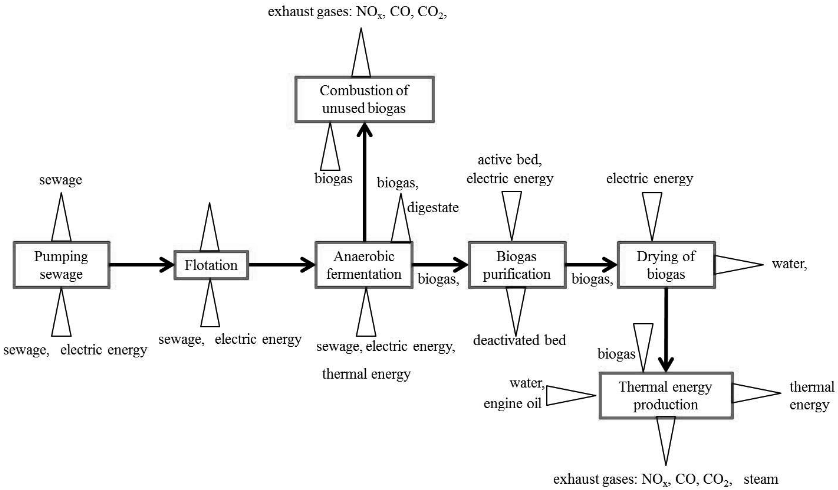

Figure 3. The overall LCI model diagram representing the anaerobic section of the waste-water treatment plant

Source: Own research based on empirical data

Summary and conclusions

Dairy wastewater treatment by anaerobic fermentation appears to be an appropriate and future-oriented technology as it mitigates environmental impact. An added benefit of using such installations is the high methane content which makes it possible to reduce the capital and operating expenditures associated not only with the biogas section but also the entire processing plant. In terms of increased production in the Chodzież dairy plant there are large amounts of waste water produced and residues are difficult to manage and are harmful to the environment. Currently, after setting the bioreactor biogas is produced from that waste. Subsequently biogas is used for their needs for heating processes, which in terms allows reducing the consumption of natural gas by about 1/5 and allows you to reduce costs limiting the negative impact on the environment at the same time. The facility produces two independent impact reducing streams. The company treatment plant with its anaerobic section is an environmentally sound method of disposing of production waste. On the other hand, the production and the subsequent use of biogas for heat generation significantly reduces the consumption of non-renewable fuel, i.e. natural gas, thereby fitting into a sustainable growth policy.

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