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Treatment of Craft Brewery Sewage with SS VF and FWS Constructed Wetland – Lab Scale Experiment

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Abstract: The problem of wastewater treatment from craft breweries emerged in Poland about 10 years ago when an increase in the number of small breweries was observed. Plants located in small towns are forced to solve the problem on their own. One of the possibilities is to use low-cost technology of constructed wetlands with subsurface and surface flow. The purpose of the research was to test the possibility of effective treatment of sewage from a craft brewery in a lab-scale research installation and to determine the parameters for designing a real scale plant. Wastewater from the Waszczukowe brewery was used in the study. The research system consisted of a retention and aeration tank, SS-VF subsurface flow and FWS surface flow beds. An innovative Certyd filling produced by LSA company was used. The high efficiency of SS-VF bed and the entire research system was found. The removal efficiency in SS VF was on average 89.7% for BOD5, 90.5% for COD, 54.6% for TN and 52.1% for TP. For whole treatment it was respectively 97.1%, 96.7%, 72.6% and 61.3%. A high organic matter removal effect was found for the SS-VF bed (87.1 g BOD_5 m^{-2} d^{-1}) and a relatively low for the FWS (3.0 BOD_5 g m^{-2} d^{-1}). The study confirmed the need for plant design based on hydraulic load and required load removed per unit area.

Keywords: craft brewery, sewage treatment, constructed wetlands,
subsurface and surface flow system

1. Introduction

According to a report by the Polish Craft Brewers Association, the share of craft beers in total beer production in Poland was about 0.4-0.5% in 2018. The estimated production was about 200000 hl with the total beer production in Polish breweries amounting to about 41 million hl in 2017. Currently, the number of craft breweries in Poland is approaching 500 (Wojtyra & Grudzień 2017).

The amount of wastewater generated by craft breweries in relation to the product unit (hl) does not differ significantly from the amount characteristic for large corporate breweries. Assuming a ratio of about 5 hl of wastewater per 1 hl of beer produced, it can be estimated that craft breweries generated about 100,000 m^3 of wastewater in 2017. While this is a small amount, it can be a significant impediment for investors who plan to locate breweries outside of urban areas without access to sewage network system. Water can be drawn from the brewery's own intakes or from the water supply network, which is usually fed by good quality groundwater, but properly addressing wastewater management is one of the most important environmental issues.

Assuming that one craft brewery in Poland produces about 3000 to 6000 hl of beer per year, the daily amount of wastewater is about 5-10 m^3. Irrespective of the size of the brewery, this sewage has to be disposed either in the sewer network and the municipal wastewater treatment plant (WWTP), or in the brewery's individual WWTP. Craft breweries located in large cities are in the best situation as they can discharge their wastewater to municipal WWTPs. Small amounts of wastewater in relation to the total amount of wastewater discharged from the city have no impact on the treatment process in large WWTPs utilizing sludge activated system. Larger breweries use anaerobic pretreatment of wastewater before its discharging into the sewer system, obtaining biogas for electricity generation (Umiejewska 2019, Simate et al. 2011, Driessen & Vereijken 2003, Enitan et al. 2014, BAT 2008, Okunola et al. 2019). In the case of small towns with daily flow up to a few hundred cubic meters per day, even a small amount of wastewater from a craft brewery can significantly interfere with the proper operation of the WWTP (Dąbrowski 2009). One solution is to use retention tanks which allow the wastewater to be evenly discharged to the sewer network and the municipal WWTP.

During authors research conducted since 2018 on the composition and treatment capabilities of craft brewery wastewater using a system based on a trickling filter and subsurface vertical flow constructed wetland (SS VF) has shown that the wastewater has significantly higher organic content and nutrient concentrations compared to domestic and municipal wastewater.

The craft brewery wastewater used in this study had values in the range of: BOD_5 1940-2360 mg O_2 dm^{-3}, COD 3600-4200 mg O_2 dm^{-3}, TN 37.2-52.0 mg dm^{-3} and TP 19.8-28.0 mg dm^{-3} (Dąbrowski & Karolinczak 2019). Similar effluent parameters are confirmed by different authors (Janczukowicz et al. 2013, Umiejewska 2019, Mielcarek et al. 2013).

A separate problem of craft breweries that is not present at large industrial breweries is the periodicity of production. A typical craft brewery is characterized by frequent production interruptions, a normal phenomenon resulting from the specific nature of these plants. However, this causes limitations in the application of wastewater treatment technology based on the sludge activated system, which requires a constant supply of wastewater. Therefore, it is advisable to look for other solutions that can be used for treatment or pretreatment of this type of brewery wastewater.

One alternative method is constructed wetlands (CWs) technology. It has a number of advantages, including being immune to periodic wastewater supplying. CWs are characterized by simple construction and operation, properly constructed can provide a high treatment effect with very low energy consumption compared to conventional systems such as activated sludge or trickling filter (Kolecka et al. 2018, Karolinczak et al. 2015). Pollutants removal is possible, thanks to creating specific conditions allowing the plants' growth, as well as intensifying the processes of oxidation, reduction, sorption, precipitation, sedimentation and assimilation. Currently, SS VFs are the most widespread and are used, among others, to treat domestic wastewater, rainwater, septage, wastewater from selected industries or specific wastewaters such as leachate from landfills, from sludge treatment (Kadlec & Wallace 2009, Karolinczak & Dąbrowski 2017, Obarska-Pempkowiak et al. 2015, Vymazal 2010, Karolinczak et al. 2020). Only a few applications of CWs can be found for treatment of brewery sewage (Massi et al. 2018, Kadlec & Wallace, 2009).

Due to limited information on the application of CWs systems for brewery wastewater treatment, it was decided to precede the real-scale studies with a laboratory-scale experiment. The objective of this study was to determine the effectiveness of a SS VF and free water surface (FWS) bed system with floating plants. The results of the research will be used to design a full scale installation for a craft brewery wastewater treatment.

2. Methods and research installation

Wastewater used in this study originated from Waszczukowe brewery with annual production of 5000 hl. It is one of the largest craft breweries in Podlaskie province. The average volume of wastewater in 2019 was about 9 m^3/d, and the ratio of wastewater volume per unit of production was 5.6 hl/hl of beer and was similar to the values characteristic for the concern breweries (Janczukowicz et al. 2013).

Wastewater treatment process studies were conducted in the laboratory of the Department of Technology in Environmental Engineering at BUT from November 2019 to March 2020. The research installation was designed by one of the authors using earlier experience with different kinds of sewage treated with CWs system. Its main elements are: SS VF planted with *Phragmities australis* and FWS with floating plants: *Salvinia natans*. The installation also includes a retention - aeration tank (RAT) and pump supplying FWS with sewage treated in SS VF. The beds were used in series. Research installation with sampling points (I-IV) is presented in Figure 1, view of the beds and cross section of SS VF in Figure 2. SS VF bed with total highest 0.8 m, was built of three layers (A, B, C) of lightweight sintered aggregate *Certyd* with a granulation of 3 to 9 mm. The use of *Certyd* instead of gravel and sand has a significant environmental impact. It is a ceramic and porous material obtained by the thermal processing of ash. It has a certificate from the National Institute of Hygiene HR/B/86/2015.

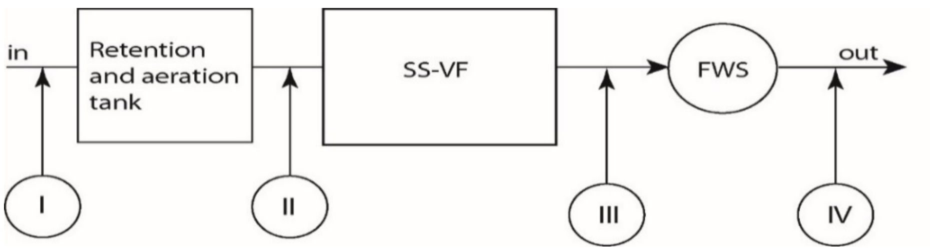

Fig. 1. Research installation with sampling points

Fig. 2. View on SS VF and FWS and cross section of SS VF

The experiment was conducted at approximately 20°C with a hydraulic load of 0.05 $m^3m^{-2}d^{-1}$ for the SS VF bed and 0.035 $m^3m^{-2}d^{-1}$ for the FWS beds. The hydraulic retention time (HRT) for the FWS was approximately 3 days. Before starting the experiment, the whole installation was started-up for one month.

2.1. Sampling and analytical procedures

During the study period, 12 test series were performed, each including the determination of raw wastewater parameters (sampling point I), wastewater feeding the SS VF and FWS (sampling points II and III) and treated wastewater (sampling point IV). Concentrations of organic matter (BOD_5, COD), total nitrogen (TN), ammonia nitrogen (NH_4-N), nitrate nitrogen (N-NO_3) and nitrite nitrogen (N-NO_2) and total phosphorus (TP) were analysed. In addition, dissolved oxygen concentration and pH were monitored. Determinations were conducted in a BUT laboratory in accordance with the procedures set out in the Regulation of the Minister of Maritime and Inland Waterway Economy from 12th July 2019 and in accordance with the American Public Health Association APHA (2005). Tests for the analysis of COD, TN, NH_4-N, NO_3-N, N-NO_2 and TP recommended by Merck were applied. Spectrophotometer Spectroquant Pharo 100 was used. BOD_5 was determined using OXI-TOP®.

The scope of the research made it possible to determine the pollutant loads removed at particular stages and in the entire treatment system. Removal efficiency was calculated as a concentration reduction according to the terminology given by Kadlec & Wallace (2009).

3. Results and discussion

The largest impact on the amount and load of wastewater generated in the brewery is generated by washing processes. This is characteristic of agri-food plants (Żyłka et al. 2020). Large breweries generally use Cleaning in Place (CIP) stations, while most small breweries do not use them. This affects possible higher raw wastewater parameters, especially TP concentration. Analyzing the parameters of raw wastewater from the Waszczukowe brewery (Table 1) it can be concluded that the values obtained do not differ from those presented by other authors dealing with wastewater from other breweries (Driessen & Vereijeken 2003, Simate et al. 2011, Enitan et al. 2014, Janczukowicz et al. 2013, Budgen & Le-Cech, 2020).

Table 1. Characteristics of raw sewage from craft brewery plant (sampling point I)

Parameter	Unit	Mean ±st. dev.	Min-max
BOD_5	mg O_2 dm^{-3}	1942 ±75	1807-2050
COD	mg O_2 dm^{-3}	3704 ±206	3480-4030
N-NH_4	mg N-NH_4 dm^{-3}	7.5 ±1.1	4.9-9.2
N-NO_3	mg N-NO_3 dm^{-3}	1.0 ±0.2	0.6-1.4
TN	mg N dm^{-3}	42.1 ±3.5	37.0-49.0
TP	mg P dm^{-3}	17.4 ±2.4	12.0-21.0

Source: own research

The analysis of the data presented in Table 1 shows that the concentration of organic matter in the brewery effluent measured by the BOD_5 and COD values is 2-3 times higher compared to the municipal wastewater. In terms of organic matter content, the raw brewery wastewater parameters are similar to those observed in the dairy and meat processing industries. The brewery wastewater does not contain, for example, fats present in dairy or meat processing wastewater (Dąbrowski et al. 2016, Struk-Sokołowska et al. 2018). Analyzing nitrogen and phosphorus it was concluded that total nitrogen concentration is lower than in municipal sewage, while the phosphorous concentration is higher (Heidrich & Witkowski 2015, Klimiuk & Łebkowska 2004). Due to the safety of the product, there is no way to decrease raw sewage parameters, which is typical of the entire food industry (BAT, 2019).

Results of laboratory scale of craft brewery treatment in SS VF and FWS are presented in Table 2.

Table 2. Characteristics of inflow to SS VF (sampling point II), outflow from SS VF (sampling point III) and outflow from FWS (sampling point IV)

Parameter Unit	Inflow to SS VF		Outflow from SS VF		Outflow from FWS	
	Mean ±st.dev.	Min-max	Mean ±st.dev.	Min-max	Mean ±st.dev.	Min-max
BOD_5 mg O_2 dm^{-3}	1883 ±86	1740-2010	141 ±9	128-160	55 ±12	38-70
COD mg O_2 dm^{-3}	3618 ±191	3390-3880	265 ±34	215-320	119 ±22	90-155
$N\text{-}NH_4$ mg dm^{-3}	5.8 ±1.3	3.7-8.1	1.0 ±0.3	0.5-1.5	0.7 ±0.3	0.3-1.1
$N\text{-}NO_3$ mg dm^{-3}	1.7 ±0.4	1.0-2.2	5.4 ±1.1	4.0-7.4	2.7 ±0.6	4.5-8.1
TN mg dm^{-3}	35.0 ±3.7	30.0-42.0	12.0 ±1.5	10.0-15.0	9.6 ±1.1	7.4-11.3
TP mg dm^{-3}	16.9 ±2.4	11.0-21.0	7.9 ±1.5	4.6-10.4	6.5 ±1.0	4.5-8.1

Source: own research

From the analysis of the results presented in Tables 1 and 2, it can be seen that retention – aeration tank does not significantly affect the reduction of wastewater parameters. For example, the average values of BOD_5 decreased by 3%, while COD only 2.3%. For TN and TP it was 16.9% and 2.8%. The role of this device is mainly to equalize the wastewater load entering the SS VF and to aerate the raw wastewater. Average dissolved oxygen in sewage discharged to SS VF was 2.0 mg O_2 dm^{-3}.

Considering the wastewater parameters shown in Table 2 and the hydraulic load, the average pollutant load of SS VF was 94.2 g O_2 $m^{-2}d^{-1}$ for BOD_5 and 180.9 g O_2 $m^{-2}d^{-1}$ for COD. Low hydraulic load (0.05 $m^3m^{-2}d^{-1}$) allowed efficient removal of organic substances. The average BOD_5 value decreased from 1883 to 141 mg O_2 dm^{-3}, while COD from 3618 to 265 mg O_2 dm^{-3}. The average load for TN and TP was 1.75 g N $m^{-2}d^{-1}$ and 0.84 g P $m^{-2}d^{-1}$. A decrease in phosphorus concentration from 16.9 to 7.9 mg P dm^{-3} was observed. Due to high organic substances concentration pollutants loads were higher in compare with municipal or household sewage treatment with CWs (Obarska-Pempkowiak et al. 2015, Kadlec & Wallace 2009, Vymazal 2010). Hydraulic load for FWS was 0.035 $m^3m^{-2}d^{-1}$ while pollutant loads were 4.9 g O_2 $m^{-2}d^{-1}$ for BOD_5 and 9.3 g O_2 $m^{-2}d^{-1}$ for COD. Respectively for TN and TP it was 0.42 g $m^{-2}d^{-1}$ and 0.3 g $m^{-2}d^{-1}$. Due to Vymazal (2010) loading rates for FWS recommended to achieve 30 mg dm^{-3} of BOD_5 in effluent are 6 g O_2 $m^{-2}d^{-1}$. During treatment in FWS, BOD_5 decreased from 141 to 90 mg O_2 dm^{-3}, while COD from 265 to 119 mg O_2 dm^{-3}. TN decreased from 12 to 9.6 mg N dm^{-3}, while phosphorus from 7.9 to 6.5 mg P dm^{-3}.

Removal efficiency obtained during research is presented in Figure 3.

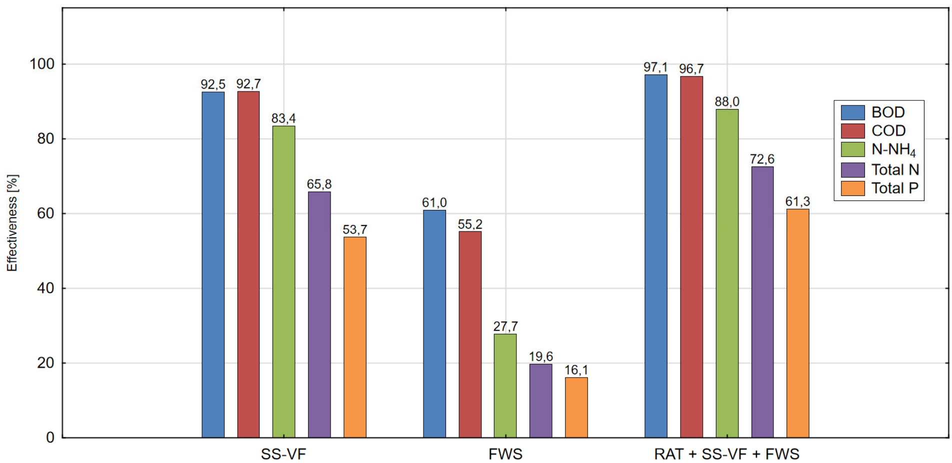

Fig. 3. Treatment efficiency of SS-VF, FWS and hybrid system

The removal efficiency for the whole treatment (RAT + SS-VF + FWS) was on average 97.1% for BOD_5, 96.7% for COD, 72.6% for TN and 61.3% for TP. The removal efficiency in SS VF bed was respectively: 89.7%, 90.5%, 54.6% and 52.1%. The treatment results achieved are similar to presented by other authors analyzing real and pilot scale systems (Kadlec & Wallace 2009). Efficiency of BOD_5, COD, TN and TP removal in FWS was respectively: 61%, 55.2%, 19.6% and 16.1%. De Stefani et al. (2011) reported efficiency of TN removal from 13 to 29% and 65% for TP in FWS, while Lopardo (2019) reached TP removal from 17.4 to 39.5%. Ozengin & Elmaci (2007) reached 50 to 95.5% efficiency for COD, 80.8 to 82.4% for TN and 71.2 to 85.4% for TP. They investigated FWS system with *Lemna minor* for municipal and industrial sewage treatment.

Table 3 shows the pollutant loads removed during SS VF, FWS and entire treatment system, which is an important parameter in evaluation of the effectiveness of CWs.

Table 3. SS VF, FWS and total load removed

Parameter	Load removed		
	SS-VF	FWS	Total
	$g\ m^{-2}\ d^{-1}$	$g\ m^{-2}\ d^{-1}$	$g\ m^{-2}\ d^{-1}$
BOD_5	87.11 ±4.02	3.00 ±0.28	90.11 ±3.93
COD	167.65 ±8.53	5.08 ±0.49	172.73 ±8.79
NH_4^+-N	0.24 ±0.05	0.01 ±0.004	0.25 ±0.05
TN	1.15 ±0.05	0.08 ±0.04	1.24 ±0.15
TP	0.45 ±0.06	0.05 ±0.02	0.50 ±0.07

Source: own research

There was a high organic matter removal effect per unit area of SS VF bed (87.11 $g\ m^{-2}\ d^{-1}$ for BOD_5) and relatively low in FWS bed (3.0 $g\ m^{-2}\ d^{-1}$ for BOD_5). The significantly lower removal efficiencies of NH_4^+- N, TN and TP were due to the low hydraulic loading and low concentrations of nitrogen and phosphorus in sewage supplying FWS. On the other hand, the main task of the entire plant was to ensure efficient removal of organic matter. Small WWTPs are obligated to remove efficiently organic matter (BOD_5 and COD), while phosphorus and nitrogen are not limited (Regulation of the Minister of Maritime and Inland Waterway Economy from 12th July 2019).

4. Conclusions

According to the authors, the problem of treating wastewater from craft breweries can be solved applying CWs method. It can be used as an individual WWTP in case of no access to a sewer system. It can be also used for craft brewery pretreatment before its discharging to small municipal WWTP. The laboratory scale tests were used to develop parameters for the real scale experiments. The main parameters for the design of such an installation should be: the hydraulic load and the pollutant loads removed per unit area of the bed. Own research has confirmed the possibility of replacing the typical SS-VF bed filling (sand and gravel) with a waste material *Certyd*. Results from this study confirm high efficiency of SS-VF bed planted with *Phragmities australis* and much lower for FWS planted with

Salvinia natans for craft brewery sewage treatment. The efficiency of organic substances removal for entire system measured by BOD_5 was on average 97.1% while for SS-VF 92.7% and 61% for FWS. TN removal was respectively 72.6%, 65.8% and 19.6%, while for TP it was 61.3%, 53.7% and 16.1%. It is recommended to design real scale system to ensure required effect of wastewater treatment during winter period only by means of SS-VF bed operation. An important aspect of the application of such low-cost system is the fact that the amount of wastewater discharged to the receiver or to the municipal WWTP can be significantly reduced in the transpiration and evaporation processes. This will be the subject of further research.

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