Rate of change in concentration of organic compounds and nutrients in municipal and dairy wastewater treated in full technical SBR scale

Joanna Struk-Sokolowska[1,*], and *Monika* Puchlik[1]

[1]Technical University Of Bialystok, Department of Technology in Engineering and Environmental Protection, Wiejska St. 45E, Bialystok 15-351, Poland

Abstract. Municipal WWTP often receive the industrial wastewater, including dairy sewage. The problem of sewage treatment from this sector of economy is not completely solved, especially in plants of medium and small milk processing capacity. The aim of the study was to determine the rate of change in organic compounds and nutrients in municipal wastewater with the participation of dairy products during the processing phases of SBR-type reactor in a technical scale. The study was conducted in WWTP in Sokolka. Rate of changes in the concentrations of organic compounds, nitrogen and phosphorus in wastewater during the processing phases of SBR reactor was determined. Presence of dairy sewage (13% volume participation) affected the decrease in the rate of changes in organic compounds concentrations defined as BOD_5 during all processing phases of SBR reactor. Significant influence of dairy sewage on rates of change in nitrogen and phosphorus compounds concentrations during filling, aeration, stirring, sedimentation and decantation phases, was found.

1 Introduction

In municipal wastewater treatment technology, the activated sludge in a batch SBR system is often used. Wastewater treatment is carried out in a single-chamber bioreactor, in which during the alternating phases, processes of integrated removal of carbon, nitrogen and phosphorus occur, as well as the distribution of treated wastewater from the process medium, takes place. There are few reports [1–3] in the literature on the rate of change in organic compounds and nutrients during SBR processing phases.

Municipal sewage treatment plants often receive the industrial wastewater, including dairy sewage. The problem of sewage treatment from this sector of economy is not completely solved, especially in plants of medium and small milk processing capacity. Dairy wastewater is characterized by high load of COD and BOD_5. This includes dissolved and crystallized fats (glycerol, triglycerides), sugars (lactose), and protein (casein) in colloidal form and as a clot. Shares of these substances can vary. Quantity of dairy sewage

* Corresponding author: j.struk@pb.edu.pl

is characterized by high seasonal variations (20% increase in spring and summer). Additional oscillations relate to the daily and hourly shift work dependent on the size, production profile, and shifts at milk processing plant [4–12]. Biological treatment of dairy wastewater is high-efficient due to the significant share of easily biodegradable substances [13–16]. It is possible to co-treat the dairy and municipal wastewater to achieve the desired C:N:P ratio in order to carry out highly effective denitrification and biological phosphorus removal. However, analysis of the up-to-date knowledge showed that there is a lack of data on the effects of dairy sewage on the efficiency of municipal wastewater treatment in sequential chambers.

The aim of the study was to determine the rate of change in organic compounds and nutrients in municipal wastewater with the participation of dairy products during the processing phases of SBR-type reactor in a technical scale.

2 Material and methods

2.1 Area of study

The study was conducted in mechanical-biological treatment plant in Sokolka. The facility consists of mechanical sewage treatment station (blocked device of type Rotomat Huber Ro5/780/2 with capacity of 120 $l{\cdot}s^{-1}$ equipped with the cylindrical sieve with a diameter of 780 mm and 2 mm clearance holes, sand traps purged from the scrubber sand RoSF4tC, fat separator, and press for dewatering of remains). Mechanically treated waste-water flows into the intermediate pumping station. They are pumped into the averaging two-chamber retention tank with an active volume of 1800 m^3. This tank is equipped with 2 hyperboidal stirrers of type HCMA with aeration grate and in mixer 2 hyperboidal stirrers of type HCM. There is the possibility of dosing the coagulants. Wastewater is pumped from the tank to the sequential biological reactors (SBR). The process of biological treatment is carried out in the cyclic system, in four cylindrical chambers of the active capacity of 1500 m^3, equipped with hyperboidal stirrers of type HCMA. Duration of a single cycle is 8 hours 10 minutes (filling phase – 0.7 h, aeration phase – 4 h, the stirring phase – 1 h, sedimentation phase - 1.5 h, decantation phase - 1 h). Oxygen conditions vary over a range from 1.8 to 4 g $O_2{\cdot}m^{-3}$. The maximum daily capacity of the plant is 6000 m^3, and the equivalent population (PE) 25070. The object receives domestic and industrial wastewater from the milk processing plant. Dairy Cooperative in Sokolka discharges sewage to municipal sewage treatment plant after the pretreatment process. Table 1 presents types of wastewater and sludge subjected to physicochemical determination.

Table 1. Types of municipal wastewater and sludge subjected to physicochemical determination.

Sample	Hour	Phase of treatment process
S1	6.00 a.m.	Raw wastewater
S2	6.20 a.m.	Wastewater after mechanical treatment collected from the retention chamber*
S3	7.00 a.m.	Wastewater from SBR (end of filling phase, before aeration phase)
S4	8.10 a.m.	Wastewater from SBR, after 60 minutes of aeration (total duration 240 min.)
S5	9.10 a.m.	Wastewater from SBR, after 120 minutes of aeration
S6	10.10 a.m.	Wastewater from SBR, after 180 minutes of aeration
S7	11.10 a.m.	Wastewater from SBR, after 240 minutes of aeration
S8	12.10 a.m.	Wastewater from SBR (end of stirring phase)
S9	1.40 p.m.	Wastewater from SBR (end of sedimentation phase – 90 minutes)
S10	2.40 p.m.	Wastewater from outlet (end of decantation phase – 60 minutes)
$S_{a.slud.}$	11.00 a.m.	Activated sludge from SBR chamber
* Periodic supply of over-sediment water from decanter centrifuge		

Table 2 shows the average flows and loads of municipal and dairy wastewater flowing into the sewage treatment plant according to operational data from 2010-2014.

Table 2. Quantities and loads of contaminants in dairy and municipal wastewater.

Qd_{max} (d-daily; max – maximum)	$m^3 \cdot d^{-1}$	6000
Qd_{av} (d-daily; av – average)	$m^3 \cdot d^{-1}$	3350
$Qd_{av\ liquid\ wastes}$ (d-daily; av – average)	$m^3 \cdot d^{-1}$	27
PE (equivalent population)		25070
$Qd_{av\ dairy}$ (d-daily; av – average)	$m^3 \cdot d^{-1}$	430
Volume share of dairy sewage in municipal wastewater	%	13
Load of BOD_5 (Biochemical Oxygen demand)	$kg \cdot d^{-1}$	1504
Load of $BOD_{5\ dairy}$	$kg \cdot d^{-1}$	103
Share of BOD_5 load of dairy sewage in municipal wastewater	%	7
Load of COD (Chemical Oxygen Demand)	$kg \cdot d^{-1}$	2811
Load of COD_{dairy}	$kg \cdot d^{-1}$	201
Share of COD load of dairy sewage in municipal wastewater	%	7

Table 3 presents selected data on the production profile of the dairy processing plant.

Table 3. Production characteristics of dairy processing plant.

Amount of processed milk [$m^3 \cdot d^{-1}$]	80.00
The ratio of wastewater produced [$m^3 \cdot d^{-1}$]	4.81
Leading products	cottage cheese, sour cream, kefir, yogurt

2.2 Analytical Methods

The scope of analytical determinations made in samples included analysis of the following indicators: BOD_5, COD, TOC, N_{tot}, P_{tot} - in wastewater; V, MLSS, SVI – in activated sludge. Analyses were carried out in accordance with APHA (2012) [17]. Based on the study results, calculations of carbon, nitrogen and phosphorus removal efficiency (total and partial), as well as the rate of change in parameters during the processing phases of SBR reactor, were carried out. Total removal efficiency was calculated from the difference of a given parameter concentration at the inlet (C_O) and outlet (C). Efficiency of the partial of organic carbon, nitrogen and phosphorus removal from wastewater was calculated from the difference of a given parameter concentration at the start (C_X) and end (C_Y) of the treatment phase.

Rate of changes in the concentrations of organic compounds, nitrogen and phosphorus in wastewater (r_V) during the processing phases of SBR reactor was determined from the formula:

$$r_V = (A - B) / T \tag{1}$$

r_V – rate of the parameter change in wastewater, $mg \cdot dm^{-3} \cdot h^{-1}$
A – concentration at the start of processing phase, $mg \cdot dm^{-3}$
B – concentration at the end of processing phase, $mg \cdot dm^{-3}$
T – durability of processing phase, h.

To determine the rate of change in parameters in wastewater relative to the concentration of activated sludge in SBR reactor (r_X) for particular processing phases, following dependence was applied:

$$r_X = [(A / X_p) - (B / X_k)] / T \tag{2}$$

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r_X – rate of the parameter change in wastewater, $mg \cdot g_{DM}^{-1} \cdot h^{-1}$
X_p – concentration of activated sludge in SBR at the start of processing phase, $g_{DM} \cdot dm^{-3}$
X_k – concentration of activated sludge in SBR at the end of processing phase, $g_{DM} \cdot dm^{-3}$.
To calculate the rates (r_V, r_X), a simplification was assumed that concentrations of organic compounds and nutrients at the end of the processing phase are equal to the concentrations at the start of the subsequent SBR processing phase. It was also assumed that changes in biomass of the activated sludge during an 8-hour SBR cycle are not significant [1, 2, 14]. Accordingly, the equation takes the following form:

$$r_X = [(A - B) / X] / T \quad (3)$$

X – concentration of activated sludge in SBR, $g_{DM} \cdot dm^{-3}$.
In order to determine the influence of dairy sewage on the rate of change in the concentrations of organic compounds and nutrients, municipal wastewater (collected before connecting with a stream of dairy sewage) was purified in a model SBR reactor presented in paper by Struk-Sokołowska and Ignatowicz [18], according to the methodology described in the publications by Struk-Sokołowska [2, 18]. Municipal wastewater treatment in a model SBR reactor was performed in this study. Processing parameters and the activated sludge were the same as in the wastewater treatment plant in Sokolka.

3 Results

Table 4 presents characteristics of activated sludge in Sokolka.

Table 4. Characteristics of activated sludge ($S_{a.slud}$) in Sokolka.

Settled sludge volume	V	$cm^3 \cdot dm^{-3}$	510.0
Concentration of solids in the sludge suspension	MLSS	$kg_{DM} \cdot m^{-3}$	3.8
Sludge Volume Index	SVI	$cm^3 \cdot g_{DM}^{-1}$	134.2

3.1 Rates of parameters change in wastewater in various stages of treatment

The rates of changes (r_V and r_X) in particular parameters of municipal wastewater with 13% share of dairy sewage are presented in Table 5.

In mixed filling phase in SBR in Sokolka wastewater is mixed with the biomass. It initiates biological reactions, degrades the organics by using residual oxygen. De-nitrification may occur in this fill. Average rate of total nitrogen removal during 40-minute filling phase in SBR content was 64.3 $mg \cdot dm^{-3} \cdot h^{-1}$ (in reference to the activated sludge biomass concentration was 16.92 $mg \cdot g_{DM} \cdot h^{-1}$). During this phase, some decrease in the total phosphorus concentration was recorded. Rate of phosphorus removal was 6.4 $mg \cdot dm^{-3} \cdot h^{-1}$ (1,68 $mg \cdot g_{DM}^{-1} \cdot h^{-1}$). Average rate of organic matter removal expresses as BOD_5 during filling phase amounted to 668.6 $mg \cdot dm^{-3} \cdot h^{-1}$ (in relation to the biomass -176 $mg \cdot g_{DM} \cdot h^{-1}$). Average rate ($r_V$) of organic matter removal determined by parameter COD during dephosphatation in SBR was 922.1 $mg \cdot dm^{-3} \cdot h^{-1}$ (242.7 $mg \cdot g_{DM} \cdot h^{-1}$).

Aeration phase in SBR in Sokolka may be mixed react or aerated react type. Mixed react allows anoxic condition to achieve de-nitrification and aerated react allows aerobic condition during aerated fill to achieve complete nitrification. The aeration phase lasting 240 minutes cause the removal of the total nitrogen from wastewater at mean rate of 1.5 $mg \cdot dm^{-3} \cdot h^{-1}$ (0.39 $mg \cdot g_{DM} \cdot h^{-1}$). It should be underlined that this rate during initial 60 minutes amounted to 7.8 $mg \cdot dm^{-3} \cdot h^{-1}$ (2.05 $mg \cdot g_{DM} \cdot h^{-1}$), while during the subsequent 180 minutes, it decreased up to 0.5 $mg \cdot dm^{-3} \cdot h^{-1}$ (0.13 $mg \cdot g_{DM} \cdot h^{-1}$) or the increase of the total nitrogen concentration at the rate of 1.2 $mg \cdot dm^{-3} \cdot h^{-1}$ (0.32 $mg \cdot g_{DM} \cdot h^{-1}$), was recorded.

With the beginning of the aeration phase, the concentration of nitrogen increased as a result of nitrification, before the settling phase. Before the decantation phase the concentration of nitrogen decreased, which may result from denitrification effected by denitrificators which contain organic matter in their cells [3]. This phase caused the total phosphorus removal from wastewater at the average rate of 1.1 $mg \cdot dm^{-3} \cdot h^{-1}$ (over 2 $mg \cdot dm^{-3} \cdot h^{-1}$ during initial 120 minutes). It should be emphasized that between 120 and 180 minute of the aeration phase, sudden release of total phosphorus at the rate of 3.2 $mg \cdot dm^{-3} \cdot h^{-1}$ was observed, and then between 180 and 240 minute of that phase, total phosphorus concentration decrease at the rate of 3 $mg \cdot dm^{-3} \cdot h^{-1}$. In order to remove phosphorus biologically, alternate aerobic and anaerobic conditions have to be ensured. During the anoxic phase, phosphorus concentration in the wastewater under treatment increased as a result of introducing raw wastewater and secondary phosphorus release to the liquid under anaerobic conditions. As the time of aeration increased, the phosphorus concentration decreased, as they were assimilated by certain bacteria strains (e.g., Acinetobacter sp., Arthrobacterglobiformis) in as much as 25% of dry cell weight [3]. Aeration of wastewater and activated sludge during 240 minutes resulted in the removal of organic matter (BOD_5) with an average rate of 1.5 $mg \cdot dm^{-3} \cdot h^{-1}$ (0.39 $mg \cdot g_{DM} \cdot h^{-1}$). During the initial and final 60 minutes of aeration, the removal rate was 2 $mg \cdot dm^{-3} \cdot h^{-1}$ (0.53 $mg \cdot g_{DM} \cdot h^{-1}$), while during the other 120 minutes, it dropped to 1 $mg \cdot dm^{-3} \cdot h^{-1}$ (0.26 $mg \cdot g_{DM} \cdot h^{-1}$). During this phase removal of organic matter referred to as COD occurred at an average rate of 1.6 $mg \cdot dm^{-3} \cdot h^{-1}$. It should be underlined that during the first 60 minutes, the rate of impurities removal was 4.7 $mg \cdot dm^{-3} \cdot h^{-1}$ (1.24 $mg \cdot g_{DM} \cdot h^{-1}$), while during the next 180 minutes of aeration, it decreased in the range from 0.9 to 0.1 $mg \cdot dm^{-3} \cdot h^{-1}$. An increase in concentration TOC was caused by carbon as similation by heterotrophic organisms. Organic matter can also be precipitated and adsorbed in activated sludge [3].

Table 5. Rates of changes in nutrients and organic compounds during processing SBR phases.

Processing phase	N_{tot}		P_{tot}		BOD_5		COD		TOC	
	r_V	r_X	r_V	r_X	r_V	r_X	r_V	r_X	r_V	r_X
filling	64.3	16.92	6.4	1.68	175.95	668.6	242.66	922.1	34.11	129.6
aeration	1.5	0.39	1.1	0.29	0.39	1.5	0.42	1.6	-0.05↑	-0.2↑
after 1/4	7.8	2.05	2.3	0.61	0.53	2.0	1.24	4.7	6.29	23.9
after 1/2	-1.2 ↑	-0.32↑	2.1	0.55	0.26	1.0	0.24	0.9	-0.11↑	-0.4↑
after 3/4	0.5	0.13	-3.2↑	-0.84↑	0.26	1.0	0.21	0.8	-0.45↑	-1.7↑
end	-1.2 ↑	-0.32↑	3.0	0.79	0.53	2.0	0.03	0.1	0.37	1.4
stirring	0.5	0.13	1.5	0.39	-	-	0.32	1.2	1.21	4.6
sedimentation	1.1	0.29	-0.1↑	-0.03↑	0.18	0.7	-1.08↑	-4.1↑	1.47	5.6
decantation	0.2	0.05	-	-	-	-	0.13	0.5	-	-
r_V - $mg \cdot dm^{-3} \cdot h^{-1}$; r_X – $mg \cdot g_{DM}^{-1} \cdot h^{-1}$, (-) – no change recorded; (↑) – increase										

In sedimentation phase in SBR in Sokolka separation of solids as settled sludge is allowed to provide clarified supernatant under quiescent condition. No influent or effluent currents interfere with settling process. In some cases gentle mixing during initial stages of settling allows clearer effluent and more concentrated sludge. Phase of sedimentation of the activated sludge in SBR caused the re-release of total phosphorus in wastewater, however, it was much lower (rate 0.1 $mg \cdot dm^{-3} \cdot h^{-1}$), than during aeration phase. The rate of changes in organic compounds defined by BOD_5 during this phase amounted to 0.18 $mg \cdot g_{DM} \cdot h^{-1}$ and the increased amounts of organic substances (as COD) in wastewater was recorded (4.1 $mg \cdot dm^{-3} \cdot h^{-1}$). The concentration of TOC decreased during the settling phase, which may have been caused by carbon consumption by denitrificators [3].

In decantation phase in SBR in Sokolka clarified treated supernatant is allowed to remove within the predetermined cycle time. Decanters are used in this process which may be of floating type or fixed type. During decantation phase total phosphorus removal and changes in organic compounds expressed as BOD_5 were not recorded in wastewater. During this phase the concentration of total phosphorus was not recorded to increase as a result of the phosphorus being released to the liquid from the precipitate [3]. Organic compounds (as COD) were removed at the rate of 0.5 $mg \cdot dm^{-3} \cdot h^{-1}$ (0.13 $mg \cdot g_{DM} \cdot h^{-1}$). Rate of total nitrogen removal was 0.2 $mg \cdot dm^{-3} \cdot h^{-1}$ (0.05 $mg \cdot g_{DM} \cdot h^{-1}$). When the accumulated organic matter was exhausted, the nitrification process took place until the end of the decantation process, in the presence of oxygen [3].

Number of literature references on the municipal wastewater treatment with a specific and strictly controlled share of dairy sewage, including biodegradation kinetics in SBR, is insufficient [1-3]. Data on qualitative and quantitative characteristics of raw dairy sewage are relatively well-documented [4-16], but at the same time there are serious gaps in relation to the municipal sewage with a specific share of industrial (dairy) wastewater. For this reason, it is impossible to compare the results with literature data.

Table 6 illustrate rates recorded in SBR-type reactors in wastewater treatment plant in Sokolka, where municipal wastewater containing dairy sewage is processed. These rates were compared to values achieved in reactors treating municipal wastewater not containing dairy sewage.

Table 6. Comparing the rate of changes (r_V, r_X) in the concentrations of compounds in wastewater and wastewater enriched with dairy sewage (mixed wastewater) during phases of the SBR cycle.

Waste-water	Parameter				
	BOD_5	COD	TOC	N_{tot}	P_{tot}
	$r_V - r_X$	$r_V - r_X$	$r_V - r_X$	$r_V - r_X$	$r_V - r_X$
Filling – 40 minutes					
mixed	668.6 – 179.95	922.1 – 242.66	129.6 – 34.11	64.3 – 16.92	6.4 – 1.68
municipal	754.3 – 198.50	831.1 – 218.71	117.4 – 30.89	62.7 – 16.5	-5.1↑ – -1.34↑
Aeration – 240 minutes					
mixed	1.5 – 0.39	1.6 – 0.42	-0.2↑ – -0.05↑	1.5 – 0.39	1.1 – 0.29
municipal	2.4 – 0.63	4.8 – 1.26	3.1 – 0.82	3.2 – 0.84	2.4 – 0.63
Stirring – 60 minutes					
mixed	-	1.2 – 0.32	4.6 – 1.21	0.5 – 0.13	1.5 – 0.39
municipal	0.1 – 0.03	0.9 – 0.24	4.0 – 1.05	0.9 – 0.24	2.2 – 0.58
Sedimentation – 90 minutes					
mixed	0.7 – 0.18	-4.1 ↑ – -1.08↑	5.6 – 1.47	1.1 – 0.29	-0.1↑ – -0.03↑
municipal	1.4 – 0.37	4.0 – 1.05	2.1 – 0.55	1.2 – 0.32	-0.8↑ – -0.21↑
Decantation – 60 minutes					
mixed	-	0.5 – 0.13	-	0.2 – 0.05	-
municipal	1.0 – 0.26	0.1 – 0.03	-0.4↑ – -0.11↑	-0.2↑ – -0.05↑	-0.2↑ – -0.05↑
r_V – $mg \cdot dm^{-3} \cdot h^{-1}$; r_X – $mg \cdot g_{DM}^{-1} \cdot h^{-1}$; (-) – no change recorded; (↑) – increase					

The presence of dairy sewage contributed to a reduction in the rate of change of organic compounds concentrations defined by BOD_5 during all processing phases of SBR reactor. Taking into account concentration of organic compounds (as COD), the 13% share of dairy sewage contributed to the decrease in the change rate only during the aeration phase. A significant influence of dairy sewage on the rate of the nitrogen and phosphorus compounds concentration change during the filling, aeration and stirring phases, was recorded. The rate of nitrogen removal during the filling phase was lower in the case of municipal wastewater treatment only. In the case of phosphorus, presence of dairy wastewater caused phosphorus binding, while for municipal wastewater, its release was observed. During the phases of aeration and stirring, reduction in the rate of phosphorus and nitrogen changes was recorded due to the presence of dairy wastewater. At the same time, during the sedimentation phase, there were comparable rate values with respect to nitrogen compounds and significantly higher rates of phosphorus release in the SBR reactor treating the municipal with no dairy wastewater. During decantation phase, impact of the dairy sewage on the rate of change in nitrogen and phosphorus compounds was smaller. Differences in the rates of change in nitrogen and phosphorus concentrations were derived from the rate of organic compounds exhausting.

The results reported in literature on biodegradation kinetics in SBR of wastewater contaminated with phenol, pesticides, herbicides as well as tannery and slaughterhouse wastewater [19-23].The rates of changes in organic compounds and nutrients of municipal wastewater with 13% share of dairy sewage can not be compared with the results of other authors.

4 Summary

The 8-hour work cycle of the SBR reactor has ensured high effectiveness of contaminants removal from municipal wastewater. Presence of dairy sewage affected the decrease in the rate of changes in organic compounds concentrations defined as BOD_5 during all processing phases of SBR reactor and the increase in organic compounds concentrations (COD) during filling, the stirring and decantation phases of SBR reactor. Exploring the kinetics of the wastewater treatment process in SBR reactor reveals characteristic changes in nitrogen concentrations for the nitrification and denitrification processes. Moreover, changes typical of phosphorus removal by phosphate microorganisms are also observable. Significant influence of dairy sewage on rates of change in nitrogen and phosphorus compounds concentrations during filling, aeration ,and stirring phases, was found. During the sedimentation phase in SBR-type reactor was found a decrease in the value of organic compounds (BOD_5, TOC) and N_{tot} and an increase of COD and P_{tot}. During decantation phase only COD and N_{tot} value decreased.

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