Carbon source recovery from excess sludge by mechanical disintegration for biological denitrification

M. Zubrowska-Sudol

ABSTRACT

The goal of the study was to evaluate the possibility of carbon source recovery from excess sludge by mechanical disintegration for biological denitrification. The total efficiency of denitrification, unit demand for organic compounds for denitrification, unit volume of disintegrated sludge and unit cost of nitrogen removal as a function of energy density used for excess sludge disintegration (70, 140 and 210 kJ/L) were analyzed. In the study a full-scale disc disintegrator was used (motor power: 30 kWh, motor speed: 2,950 rpm). It was shown that the amounts of organic compounds released from the activated sludge flocs at all tested levels of energy density are high enough to be used to intensify the removal of nitrogen compounds from wastewater. It was also documented that the energy density provided during process of disintegration was an important factor determining the characteristics of organic compounds obtained under the disintegration for their use in order to intensify the process of denitrification. The highest value of total efficiency of denitrification (50.5 ± 3.1 mg N/L) was obtained for carbon source recovery from excess sludge at 70 kJ/L, but the lowest unit cost of nitrogen removal occurred for 140 kJ/L (0.0019 ± 0.0011 EUR/g N).

Key words | carbon recovery, carbon source, denitrification, excess sludge, mechanical disintegration

M. Zubrowska-Sudol
Faculty of Building Services, Hydro and Environmental Engineering,
Warsaw University of Technology,
Warsaw,
Poland
E-mail: *monika.sudol@pw.edu.pl*

INTRODUCTION

One of the new challenges in sludge management is acting in accordance with the rules of a circular economy. The example of such action is recovery of soluble biodegradable organic compounds from activated sludge flocs and using them as a substrate for intensification of denitrification (Biradar *et al.* 2010; Yi *et al.* 2017). In order to release soluble organic compounds the disintegration of excess sludge can be used. The idea of this process is the destruction of sludge structure and the change of its physicochemical properties using the additional energy (Zhang *et al.* 2007). However, not only organic carbon but also nutrients (nitrogen and phosphorus compounds) are released from the sludge. Thus the use of disintegrated sludge as a carbon source for denitrification results in an increase of biological reactor loading by the nutrients and may lead to worse efficiency of N removal from wastewater. Such a phenomenon was noted by Meng *et al.* (2013), who used ozonation as a method for sludge disintegration. The authors hypothesized that as a result of ozonation, performed with low ozone doses, mainly not easily biodegradable compounds with long molecular chains were produced that negatively influenced N removal. On the other hand, Park *et al.* (2011) documented that application of the supernatant, separated from the ozonated sludge, allowed for increase in the efficiency of denitrification, which resulted in a decrease in concentration of total nitrogen in the treated wastewater.

It is worth stressing that most of the literature indicates that using the disintegrated sludge as a carbon source can cause an increase in the efficiency of nitrogen removal (Park *et al.* 2011; Yan *et al.* 2013; Gaopeng *et al.* 2016; Yi *et al.* 2017). This is also confirmed by our own research (Zubrowska-Sudol & Walczak 2015). After using disintegrated sludge, denitrification effectiveness increased from 49.2 ± 6.8% to 76.2 ± 2.3%, resulting in a total nitrogen decrease in effluent of 21.3 mg N/L. It was also documented that use of disintegrated sludge contributed to an increase in biological phosphorus removal effectiveness (from 28.1 ± 11.3% to 96.2 ± 2.5%), resulting in a drop of the PO_4^{3-}-P concentration in the effluent of 6.05 mg PO_4^{3-}-P/L (Zubrowska-Sudol & Walczak 2015). Moreover, some authors emphasize

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that with disintegrated sludge much higher rates of denitrification can be achieved than with acetate, which is widely accepted as a readily available source of organic carbon (Soares *et al.* 2010). These positive observations provide the basis for the belief that the use of disintegrated excess sludge as an alternative source of organic carbon for the intensification of nitrogen removal from wastewater has potential for application. Also, following the current trend in EU environmental policy, to create a circular economy, it becomes an attractive solution for wastewater treatment plant (WWTP) operators. There is unfortunately still a lack of work aimed at determining the parameters that could be used to make the decision to choose such a solution or to design a technological process. These aspects have prompted the author to undertake research aimed at identifying significant parameters characterizing the denitrification process in which a mechanically disintegrated excess sludge would be used as a carbon source. In this study the total efficiency of denitrification, unit demand for organic compounds for denitrification, unit volume of disintegrated sludge and unit cost of nitrogen removal as a function of energy density used for excess sludge disintegration (i.e. the amount of energy relating to 1 L of disintegrated sludge) were analyzed. These parameters allow for a deeper understanding of the denitrification process and are also significant in the practical applications.

MATERIALS AND METHODS

Materials

For carbon source recovery thickened excess sludge was used. It originated from biological nutrient removal WWTP, MUCT (population equivalent = 53,040). At this plant, sludge is concentrated by a belt-press. During the experiment the total solids were 4.73–6.29%.

Batch reactors for denitrification efficiency tests were inoculated with activated sludge from the same WWTP, which guaranteed the presence of denitrifiers in the biomass.

Carbon source recovery from excess sludge by mechanical disintegration

To recover soluble organic compounds from thickened excess sludge, the mechanical disintegration was used. The process was performed in a full-scale disc disintegrator driven by a motor with a power of 30 kW and speed of 2,950 rpm. It consists of three discs: two fixed (guide discs) and one rotating connected with a shaft driven by an electric motor (patent no. 211672, Poland).

The disintegrations were carried out by repeated feeding the disc disintegrator with a 60-litre sample of thickened excess sludge. The device was operating at a sludge throughput of about 3.0 m^3/h. The process was carried out in a closed circle. After introducing a selected amount of energy, expressed as energy density (ε_L: 70, 140 and 210 kJ/L), to the sludge under the disintegration process, a 2.0 L sample of disintegrated sludge was collected from a continuously stirred buffer tank. Immediately after this the liquid (subsequently called filtrate) was separated from the sludge in each sample. For this purpose the sludge was centrifuged for 30 min at 19,621 *g* (centrifuge MPW-350) and then filtered with 0.45 μm filters. In the filtrate soluble chemical oxygen demand (SCOD) and soluble total nitrogen (STN) were measured.

The next day the sludge disintegration at different energy density levels was used to carry out batch denitrification efficiency tests. The time elapsed from the end of disintegration to the start of denitrification efficiency tests was no longer than 18 hours. Sludge was stored in a temperature of 4 °C (it was verified that under such conditions the characteristics of disintegrated sludge will not change).

Batch denitrification efficiency test

The principle of the batch denitrification efficiency (BDE) tests, developed by the author of the paper, was to measure the total amount of nitrate nitrogen possible to remove from wastewater at a specified initial load of soluble organic compounds introduced into the reactor with sludge previously subjected to the mechanical disintegration. Each time, as a source of organic carbon, a sludge was used, disintegrated at the following three levels of energy density: 70, 140 and 210 kJ/L, and at the same time a control test, without adding disintegrated sludge into the reactor, was carried out. Nine repetitions of such experiment were conducted at 1-month intervals (for each of them a new portion of thickened excess sludge was delivered).

Prior to performing the BDE test the activated sludge sample, forming inoculum for the reactor test, was aerated for 18 h in order to oxidize the endogenous organic compounds which were potentially present in the cells of denitrifying bacteria. The single test was carried out in a beaker with a working volume of 3 L at temperature of 19 °C (laboratory air-conditioning). The contents of the beaker were continuously mixed using a magnetic stirrer.

The activated sludge (inoculum) was added to the beaker in an amount sufficient to provide a biomass concentration at a level of 2.5 grams of mixed liquor suspended solids per litre. Then the beaker was filled with dechlorinated tap water. Next, the prepared sample was deoxidized using gaseous nitrogen. It was applied over the surface of the liquid for the duration of the test; thus the possibility of atmospheric oxygen diffusion was eliminated. Before starting the test, disintegrated sludge was added to the batch in an amount sufficient to provide the initial concentration of SCOD at a level of 120 mg SCOD/L. Furthermore, KNO_3 solution was added in an amount corresponding to 30 mg NO_3^--N/L. This solution was added several times during the test to ensure the concentration of nitrates at a level not less than 10 mg NO_3^--N/L, so that the denitrification efficiency was not limited by the presence of electron acceptors. The samples were collected every 30 min from the reactor and immediately filtered with 0.45 μm syringe filters; then the nitrites and nitrates were measured. Additionally, SCOD was determined in the selected samples. The test was carried out until it was determined that the concentration of nitrates remained at the same level, which was interpreted as the end of the denitrification process (according to the assumption it was due to the depletion of organic carbon compounds).

The control test was conducted in an analogous way with the difference that no disintegrated sludge was introduced into the reactor. In this case, the samples from the reactor were taken every 30 or 60 minutes, and observations were carried out for as long as the duration of the tests performed with the addition of disintegrated sludge. The goal of this test was, firstly, to check whether the initial aeration of activated sludge allowed for the oxidation of the storage substances present in the cells of the denitrifying microorganisms and, secondly, to determine the extent to which the autoxidation of the biomass could lead to the formation of additional organic compounds that can be used by the denitrifying microorganisms. It has been assumed that the lack of significant NOx concentration changes will prove that NOx changes observed in other reactors are due to the use by denitrifying microorganisms of the organic compounds introduced with disintegrated sludge.

Analytics

All chemical analyses were performed in duplicate in accordance with APHA (1998) standard methods.

Calculation

Total efficiency of denitrification ($E_{Den.}$) was defined as the amount of NOx-N removed based on the unit of working volume of the test reactor:

$$E_{Den.} = \sum_{i=1}^{i=n} \Delta NO_x\text{-N} \ \ [\text{mg } NO_x\text{-N/L}] \tag{1}$$

where:

ΔNO_x-N – the decrease of NOx-N/L concentration determined between successive sampling from the test reactor [mg NO_x-N/L]

i – the number of the period between successive sampling from the test reactor.

Using disintegrated sludge as an additional source of organic carbon to support the denitrification process, it should be considered that, together with this, a certain amount of nitrogen compounds is introduced to the biological reactor that in fact also has to be removed in biological nitrogen removal processes, causing a need for a sufficient amount of organic compounds in the wastewater. In this study therefore a corrected efficiency of denitrification ($E'_{Den.}$) was proposed, being the difference in the total denitrification efficiency ($E_{Den.}$) and the amount of nitrogen compounds introduced into the test reactor with the disintegrated stream (N_{Sludge}):

$$E'_{Den.} = E_{Den.} - N_{Sludge} \ \ [\text{mg } NO_x\text{-N/L}] \tag{2}$$

Based on $E'_{Den.}$, unit carbon source demand for the denitrification process (d_{SCOD}) was calculated:

$$d_{SCOD} = \frac{SCOD_0}{E'_{Den.}} \ \ [\text{g SCOD/g N}] \tag{3}$$

where:

$SCOD_0$ – the initial value of the SCOD in test reactor [g SCOD/L].

Taking into account the values of d_{SCOD} and the value of SCOD in the sample of disintegrated sludge used as the source of organic carbon ($SCOD_{Dis.Slugde}$), the unit volume of disintegrated sludge ($v_{Dis.Sludge}$) was determined:

$$v_{Dis.Sludge} = \frac{d_{SCOD}}{SCOD_{Dis.Sludge}} \ \ [\text{m}^3/\text{g N}] \tag{4}$$

Unit cost of nitrogen removal using disintegrated sludge as organic carbon source (c_N) was calculated from the equation:

$$c_N = v_{Dis.Sludge} \cdot c_{Dis.Sludge} \text{ [EUR/g N]} \quad (5)$$

where:

$c_{Dis.Sludge}$ – costs of the disintegration [EUR/m^3],
$c_{Dis.Sludge} = \varepsilon_L \cdot c_{energy}$; ε_L – energy density used for disintegration [kJ/L], c_{energy} – price of electricity (in the calculation 0.0221 EUR/kJ was accepted, the net price obtained from the WWTP operator).

Statistics

Statistical analysis of the results was performed using STATISTICA 10.0 PL software. Verification of the hypothesis for each investigated variable distribution was determined based on the Shapiro–Wilk test. Analysis of variance for a single factor was performed to find the sensitivity of differences between variables, in which energy density used for sludge disintegration was a group variable. Efficiency of denitrification, unit carbon source demand, unit volume of disintegrated sludge and unit cost of nitrogen removal were, in turn, dependent variables. Validation of variance homogeneity in groups was performed using Levene's test. The RIR Tukey test was used to determine the sensitivity of differences between the analyzed variables. The level of sensitivity was assumed to be $\alpha = 0.05$ in the tests.

RESULTS AND DISCUSSION

Efficiency of denitrification

Figure 1 shows the results of an exemplary experiment whose purpose was to determine the efficiency of denitrification carried out using the disintegrated sludge as organic carbon source. Very low NOx-N decrease observed in the control sample (without the addition of disintegrated sludge) indicates that the biomass used for the tests was 'free' of intracellular organic compounds, which are a potential source of organic carbon for denitrification bacteria. It also shows that despite the long duration of the experiment, a significant production of organic compounds as a result of 'spontaneous' hydrolysis of sludge did not occur – compounds which could be used in the denitrification process. Therefore, it can be assumed that the changes observed in other trials resulted from the use of organic compounds introduced into the reactors with disintegrated sludge by the denitrifying bacteria.

It is well known that the disintegration of excess activated sludge, apart from organic matter release from the flocs, leads to a significant increase in the STN concentration in the aqueous phase of the sludge (Table 1). Therefore, to be able to consider a process of sludge disintegration as an alternative method of obtaining the source of organic carbon, the amount of dissolved organic compounds recovered from sludge should significantly exceed the demand for organic carbon to remove nitrogen compounds released from activated sludge flocs. From Figure 2, it is evident that the values $E_{Den.}$ were always significantly higher than the amount of nitrogen introduced into the reactor with disintegrated sludge. Thus, the disintegration of excess sludge can be considered as an alternative method of obtaining organic carbon source for denitrification support. It was also documented that $E_{Den.}$ was dependent on the energy density used in the sludge disintegration. The highest value of this parameter occurred for the energy density of 70 kJ/L, and decreased with increasing energy density. To explain this phenomenon it has been taken into account that, despite the fact that the test reactors received always the same amount of soluble organic compounds (expressed as a fraction of COD with a diameter less than or equal to 0.45 μm), disintegrated sludge remained a source of insoluble organic compounds that after enzymatic hydrolysis could be used in the process of denitrification. As a confirmation of this thesis the work of Zielewicz (2007) could be cited, documenting that the process of disintegration allows for a significant increase in susceptibility of sludge to the hydrolysis process. Since the largest volume of the disintegrated sludge (and thus the highest load of organic compounds in the form of suspensions and colloids) was introduced into the test reactor for samples in which, as organic substrate, the sludge disintegrated with an energy density of 70 kJ/L was used, it is likely that higher values of $E_{Den.}$ obtained for $\varepsilon_L = 70$ kJ/L were associated with higher load of organic compounds available for the denitrifying bacteria. The surplus of these compounds resulted from the possibility of transforming the colloidal and suspended organic substances contained in the disintegrated sludge to compounds directly assimilated by the microorganisms. The observed phenomenon could also be the effect of the different chemical nature of the soluble organic compounds released from the sludge flocs at various energy density, and hence their various properties as organic substrates in the denitrification

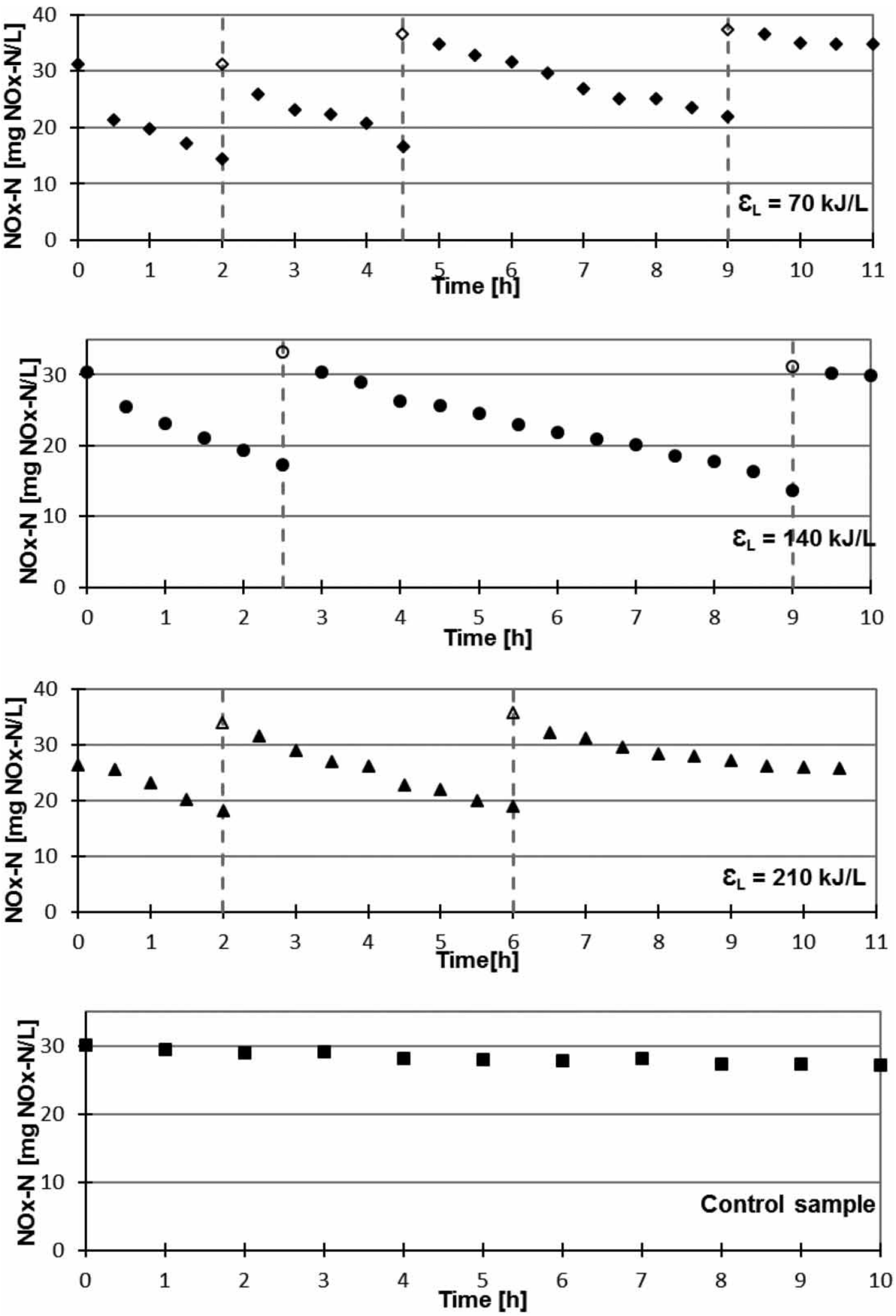

Figure 1 | Results of the sample batch denitrification efficiency tests. ◇ ○ △: the theoretical concentration, determined at the time of adding to the test reactor a nitrate solution; it expresses the value of the NOx-N which would be in the reactor after adding the nitrate solution, if biological processes did not occur in the reactor. ◆ ● ▲ ■: the actual concentration.

process. So far the failed to identify all the organic compounds released from activated sludge flocs through a process of disintegration. They are known to be a mixture of various organic compounds, allowing a relatively high denitrification rate to be obtained in comparison to other sources of organic compounds (Soares *et al.* 2010). Research of Kampas *et al.* (2007) showed that SCOD present in the disintegrated sludge included protein (30%),

Table 1 | Value of chemical indicators in centrifuged and filtrated samples after introducing a selected amount of energy to the sludge under the disintegration process

		Energy density		
Indicator	**Unit**	**70 kJ/L**	**140 kJ/L**	**210 kJ/L**
SCOD	mg O_2/L	2,047 ± 558	6,051 ± 1,582	8,091 ± 1,304
STN	mg N/L	258 ± 52	535 ± 149	709 ± 110
SCOD:STN	–	7.87 ± 1.12	11.39 ± 0.96	11.41 ± 0.63

Average ± standard deviations ($n = 9$).

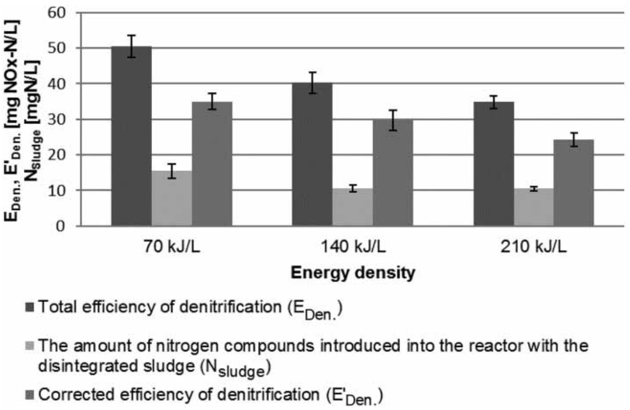

Figure 2 | Denitrification efficiency with thickened excess activated sludge disintegrated under different energy density as carbon source.

carbohydrates (13%), and volatile fatty acids (12%), and 45% of the organic compounds was not identified. As a comparison it is worth mentioning the results of Soares *et al.* (2010), who reported that the main product of acid fermentation of primary sludge was volatile fatty acids. These compounds accounted for 69% to as much as 94% of the SCOD.

Similarly to total efficiency of denitrification, for the corrected efficiency of denitrification ($E'_{Den.}$) RIR Tukey test results showed that between values of the parameter determined for the analyzed level of energy density, there are statistically significant differences, confirming that ε_L is the factor determining $E_{Den.}$ and $E'_{Den.}$ (Table 2). The highest value of $E'_{Den.}$ was also obtained for energy density of 70 kJ/L (Figure 2). An interesting observation was a decrease in the percentage difference between $E'^{70kJ/L}_{Den.}$ and $E'^{140kJ/L}_{Den.}$ in relation to percentage difference determined for $E^{70kJ/L}_{Den.}$ and $E^{140kJ/L}_{Den.}$. The average value of total efficiency of denitrification determined for the sludge subjected to disintegration at energy density of 140 kJ/L was approximately 20% lower than for the sludge disintegrated at an energy

Table 2 | Results of RIR Tukey's test for the variables characterizing denitrification process (bold results indicate the significant differences between the values of the dependent variables obtained for the compared energy density levels, which are a grouping variable)

	Compared energy densities		
Dependent variables	**70 kJ/L and 140 kJ/L**	**70 kJ/L and 210 kJ/L**	**140 kJ/L and 210 kJ/L**
N_{Sludge}	**0.000129**	**0.000129**	0.994552
$E_{Den.}$	**0.000129**	**0.000129**	**0.000835**
$E'_{Den.}$	**0.000275**	**0.000129**	**0.000270**
d_{SCOD}	**0.030547**	**0.000129**	**0.000136**
$v_{Dis.Sludge}$	**0.000129**	**0.000129**	0.845520
c_N	**0.034800**	0.992106	**0.045082**

density of 70 kJ/L, whereas the difference between average values of corrected denitrification efficiency was approximately 15%. Observed relationships were associated with the values of the SCOD:STN ratio in disintegrated sludge entering the reactor test as a carbon source. Sludge disintegrated at energy density of 70 kJ/L had lower SCOD:STN values than sludge disintegrated at 140 kJ/L (Table 1), which meant that by introducing into the reactor the same load of organic compounds, a larger load of STN was introduced (Figure 2).

Comparing the average values of $E^{70kJ/L}_{Den.}$ and $E^{210kJ/L}_{Den.}$ and, respectively, $E'^{70kJ/L}_{Den.}$ and $E'^{210kJ/L}_{Den.}$, it was found that in both cases the efficiency of denitrification determined for the tests in which sludge disintegrated at energy density of 210 kJ/L was used as a source of organic carbon was approximately 30% lower than the values of these parameters determined for sludge subjected to disintegration at energy density of 70 kJ/L.

Unit carbon source demand and unit volume of disintegrated sludge for denitrification

The lowest value of unit carbon source demand (d_{SCOD}) occurred for $\varepsilon_L = 70$ kJ/L, and it increased with increasing ε_L (Figure 3(a)). A significant relationship between an increase of d_{SCOD} and an increase of energy density (from 70 kJ/L to 140 kJ/L or to 210 kJ/L, and from 140 kJ/L to 210 kJ/L) was confirmed by statistical analysis (Table 2).

Values of d_{SCOD} and SCOD in the sample of disintegrated sludge used as the source of organic carbon for denitrification affect the unit volume of disintegrated sludge necessary to remove 1 gram of nitrate nitrogen

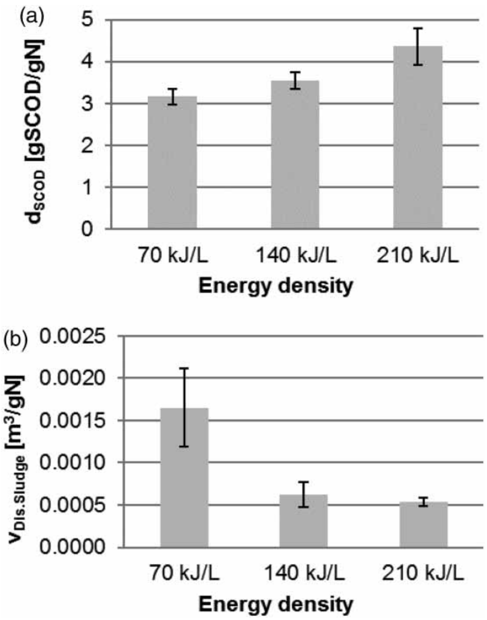

Figure 3 | Unit carbon source demand (a) and unit volume of disintegrated sludge (b) for denitrification in relation to the energy density used in the disintegration process of thickened excess activated sludge.

($v_{Dis.Sludge}$) from the treated wastewater, which is a crucial parameter when making an application decision, as it expresses the volumetric flowrate of the disintegrator. The minimum value of $v_{Dis.Sludge}$ was obtained for an energy density of 210 kJ/L (Figure 3(b)). It resulted mainly from relatively high content of soluble organic compounds in disintegrated sludge for this energy density (Table 1). This situation occurred despite the fact that sludge subjected to the disintegration at this level of energy density was characterized by the highest values of the unit demand for organic compounds (Figure 3(a)). Taking into account the results of statistical analysis, there were no significant differences between $v_{Dis.Sludge}^{210kJ/L}$ and $v_{Dis.Sludge}^{140kJ/L}$ (Table 2). However, using a sludge subjected to disintegration with an energy density of 70 kJ/L as a source of organic compounds for the denitrification, the required values of $v_{Dis.Sludge}^{70kJ/L}$ increased up to 3.06 times in relation to $v_{Dis.Sludge}^{210kJ/L}$ and 2.66 times in relation to $v_{Dis.Sludge}^{140kJ/L}$ (considering the average value of the parameter). RIR Tukey test results confirmed the existence of statistically significant differences between the values of $v_{Dis.Sludge}^{70kJ/L}$ and $v_{Dis.Sludge}^{140kJ/L}$ as well as $v_{Dis.Sludge}^{70kJ/L}$ and $v_{Dis.Sludge}^{210kJ/L}$ (Table 2).

Based on the obtained results also the amount of utilized organic carbon has been determined per unit of removed nitrate nitrogen, named the utilization of organic carbon (ΔCOD/ΔN) (Table 3). Values ΔCOD/ΔN determined for the excess sludge disintegrated at all levels of the analyzed energy density were lower than values of this parameter presented in the literature for other sources of organic carbon. This observation suggests that the organic compounds present in the disintegrated sludge are more 'efficient' in the denitrification process in relation to the other sources of organic compounds. Analyzing the data in Table 3 it can be noticed that the ΔCOD/ΔN determined for the same sources of organic compounds are in quite a wide range, making it difficult to properly discuss results in reference to observations of other researchers. Thus, taking up such discussion it should be remembered that the ΔCOD/ΔN is affected not only by the type of the analyzed source of organic carbon, but also by the type of denitrifying microorganisms present in the activated sludge and quantitative relationships between different groups of these microorganisms. Therefore, only if the tests are carried out on the same batch of sludge, can it be concluded that the kind of organic carbon source is the only variable affecting the obtained values of ΔCOD/ΔN.

Table 3 | The utilized carbon source per amount of nitrogen removed through denitrification (ΔCOD/ΔN)

Carbon source	ΔCOD/ΔN g COD/g NO_3^--N	References
Disintegrated thickened excess sludge	1.25–1.59 (70 kJ/L) 2.08–2.46 (140 kJ/L) 1.83–2.32 (210 kJ/L)	This study
Distillery wastewater	11.1–12.7	Swinarski *et al.* (2009)
Brewery wastewater	6.5–20.8	
Wastewater from a fish-pickling process	11.7–13.1	
Fusel oils	8.1–10.7	Mąkinia *et al.* (2011)
Ethanol	2.9–4.1	

Unit cost of nitrogen removal

For practical application, apart from volume of disintegrated sludge, the unit cost of nitrogen removal (c_N) is also meaningful. This parameter depends on the following factors: (1) the price of electricity, which determines the costs of the disintegration of a specific volume of sludge; (2) the unit volume of disintegrated sludge. The lowest cost was obtained for energy density of 140 kJ/L (Table 4). It was due to significantly lower value of unit volume of sludge compared to the value of this parameter determined for 70 kJ/L and due to lower cost of the sludge disintegration at 140 kJ/L compared to 210 kJ/L, at the comparable values of unit volume of the disintegrated sludge for these energy densities. The results from

Table 4 | Unit costs of disintegration and nitrogen removal with disintegrated sludge as a carbon source under different levels of energy density

		Energy density [kJ/L]		
Specification		**70**	**140**	**210**
Cost of the disintegration $c_{Dis.Sludge}$ [EUR/m^3]		1.55	3.10	4.65
Unit cost of nitrogen removal c_N [EUR/g N]	min.	0.0016	0.0013	0.0022
	max.	0.0037	0.0028	0.0028
	average	0.0026	0.0019	0.0025
	standard deviation	0.0015	0.0011	0.0004
Number of tests	9	9	9	

the RIR Tukey test indicated that the unit cost of nitrogen removal for energy density of 140 kJ/L was statistically different than that of the other energy density (Table 2). In contrast, there was no statistical difference between c_N for energy input regimes of 70 and 210 kJ/L.The author also attempted to compare the unit costs of nitrogen removal, which a WWTP would sustain using disintegrated sludge as a source of organic carbon, with the cost of purchasing conventional external carbon sources such as methanol, ethanol and acetic acid. Table 5 lists the values of the parameters used in calculations. Since no studies have been performed to identify the needs of methanol, ethanol and acetic acid for denitrification, these values have been assumed based on the literature data (Christensson *et al.* 1994; Nyberg *et al.* 1996; Kim & Son 2000; Ledwell *et al.* 2011). The purchase cost of these compounds was obtained from the company distributing the external sources of organic carbon. It should be noted that these are average prices, taking into account the various commercial offers. They were determined assuming a single purchase of 1,000 litres of raw substance and do not include transport costs.

Table 5 | Unit costs of nitrogen removal with methanol, ethanol and acetic acid as external carbon source

	Organic carbon source		
Specification	**Methanol**	**Ethanol**	**Acetic acid**
COD [g/m^3]	1,400,000	1,800,000	600,000
Price [EUR/L]	0.5	1.09	0.41
Unit carbon source demand for denitrification[a] [g COD/g N]	3.5–4.67	3.85–4.4	3.1–3.7
Unit cost of nitrogen removal [EUR/g N]	0.0009–0.0012	0.0023–0.0026	0.0021–0.0025

[a]Values assumed basing on the literature data (Christensson *et al.* 1994; Nyberg *et al.* 1996; Kim & Son 2000; Ledwell *et al.* 2011).

The obtained results (Tables 4 and 5) indicate that the use of the disintegrated sludge as organic carbon source to support the denitrification process generates comparable costs as the use of ethanol and acetic acid. It is, however, far more expensive than the use of methanol. An important advantage of disintegrated sludge in relation to conventional sources of organic carbon (even those that generate lower costs) is the recycling of waste produced in the WWTP, which is consistent with the current priorities of the environmental policy of the European Union and the principles of sustainable development.

CONCLUSIONS

1. The amounts of organic compounds released from the activated sludge flocs at all tested levels of energy density are high enough to be used to intensify the removal of nitrogen compounds from wastewater. Disintegrated thickened excess sludge can therefore be considered as an alternative source of organic carbon, and its usage as a form of recycling of waste generated in the wastewater treatment process.
2. The energy density provided during the process of disintegration is an important factor determining the characteristics of organic compounds obtained under the disintegration for their use in order to intensify the process of denitrification. The value of this parameter impacts the efficiency of denitrification, unit demand for the organic compounds, unit volume of disintegrated sludge, and the unit cost of removal of nitrogen.
3. Due to the heterogeneous composition and structure of the thickened excess sludge, and thus its varying susceptibility to disintegration, it is recommended that before implementation of the method the research phase should be taken into account, aimed at finding the energy density at which disintegration will be carried out and determination of the daily volume of disintegrated sludge necessary to remove an assumed amount of nitrogen from the wastewater.

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