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SEWAGE SLUDGE AND FOAM MANAGEMENT IN ENHANCED BIOLOGICAL NUTRIENTS REMOVAL PLANT (EBNRP)

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Abstract: Most often sewage treatment and sludge disposal are handled as two separate technological parts of treatment plants. Attempts are made to change the practice. Keeping the standards of treated sewage is the primary objective, and sewage sludge is a by-product which has to be get rid of. The environmental consequences of various procedures of sludge disposal are rarely considered. On the other hand, incorporation of sludge handling procedures in the processes of sewage treatment can result in cost savings and be environmentally friendly. In the presented paper, suggestions are given on possibilities of closer integration of sewage and sludge treatment, based on experiments. Research aimed at sewage sludge quantity minimization and quality upgrading, recovery of phosphorous and efficient nitrogen removal. Appearing occasionally scum floating over biological sewage treatment units was shown to be considered as an integrated part of sewage treatment and sludge handling at EBNRP's.

INTRODUCTION

Activated sludge is the most widely used biological waste water treatment process. Independently of the type of the activated sludge process applied, there is always a certain amount of excess sludge produced to be wasted. Even at very low organic substrate load there is a yield coefficient of about 0.4. For conventionally activated sludge with a load of about 0.5 g BOD/(g·d), the yield coefficient can be as high as 0.8.

With the introduction of biological sewage treatment aiming at nutrients removal (nitrogen and phosphorous) in addition to organic substrates removal (expressed as BOD or COD), denominated as EBNRP's the first mechanical stage of sewage treatment is most often omitted. The main reason is supplying sufficient organic substrate (organic carbon) for efficient denitrification (nitrogen removal). That approach resulted in production of distinctly larger amounts of surplus activated sludge to be disposed, which is difficult to dewater.

Also phosphorous removal can contribute distinctively to the amount of surplus activated sludge to be wasted. Although newly constructed wastewater treatment plants are designed for biological phosphorous removal, the prevailing practice is phosphorus precipitation with ferrous or aluminum salts. As a result additional sludge to be wasted is produced. If supporting the advanced biological nutrients removal process with chemical precipitation of phosphorous, an increase of waste activated sludge by about 6 kg TS/kg $P_{removed}$ is possible. The additional amount of sludge to be disposed will be about 15%.

Treatment and disposal of excess sludge from waste water treatment plants is costly and simple land fill or direct agriculture application methods can no longer be used in Europe. Therefore, sludge minimization is at present of paramount importance. An overview of possible to be applied methods of sludge minimization was given by Wei *et al.* [23].

Anaerobic sewage sludge digestion if composed mainly of preliminary sludge (retained in primary settling tanks) with a part of surplus activated sludge is recognized as an effective process, resulting in an "acceptable", almost odorless sludge, readily dewatering and drying. After eventual additional conditioning, agricultural use was widely practiced. The advantage of anaerobic sludge digestion is biogas production of high energetic value.

Anaerobic digestion of surplus activated sludge as a solely substrate is less effective, both in quality of digested sludge and the amount of produced energy (biogas). Also in addition to higher content of phosphorous in activated sludge microorganisms' precipitation of intregit and struvit become a serious problem of pipe and peripheral equipment clogging. At EBNRP scum is often formed at bioreactors surfaces and entering anaerobic digesters cause foaming, minimizing the operational (effective) volume and affecting negatively mixing efficiency of the digesters' content.

ANAEROBIC SLUDGE DIGESTION – UPGRADING THE HYDROLYSIS STEP

The microbiology of anaerobic digestion is complex, involving several bacterial groups. Four major steps can be distinguished. The first step is solubilisation of insoluble particulate matter and biological decomposition of organic polymers to monomers or dimmers. This step is denominated as the hydrolysis step. The second and the third steps, acidogenesis and acetogenesis, allow production of methane in the following fourth step.

The first stage of anaerobic digestion, the hydrolysis step, is regarded as the rate limiting step in the degradation of complex organic compounds, such as waste activated sludge. Therefore, several techniques have been investigated to upgrade the effects of organics decomposition by introduction of pretreatment hydrolysis.

Much attention is given to thermal hydrolysis as an alternative pretreatment process. In fact, thermal pretreatment increases the rate of hydrolysis, thus leading to a greater extent of solubilisation of the available chemical oxygen demand. This allows for enhanced rates of degradation in the process of anaerobic sludge digestion. The developed and commercialized CAMBI process [11] can be an example of thermal treatment which precedes sludge digestion. It is considered to be a thermal disintegration procedure which substantially hydrolyses the sludge. Saturated steam is used for sludge hydrolysis at a temperature of 165°C at 6 bar pressure for 30 minutes without addition of chemicals.

The thermal pretreatment results in a substantial biogas production increase. Also a 60% VS reduction with the digester loading of 5–6 kg VS/m^3 per day is possible. The final product is fully pasteurized – free of all known pathogens. Typically, thermal pretreatment allows for reduction of the digesters volume in comparison to conventional process.

However, it has been documented that thermal pretreatment of sludge is responsible for the formation of refractory dissolve organic compounds [3, 5]. Among other refractory compounds, melanoidin has been hypothesized to be produced, resulting in dark brown liquor [17]. After commissioning of the CAMBI process at the treatment plant

Oxley Creek – Australia [4], a distinctive increase of color and dissolved nitrogen in the liquor has been experienced. Color produced during the thermal hydrolysis of waste activated sludge was found [4] to be highly dependent on the operating temperature of the process. By decreasing the thermal hydrolysis process operating temperature from 165 to 140°C, for a reaction period of 30 min, a reduction of 70% of the color was obtained.

Thermal pretreatment, as documented [1], at a temperature of 121°C effectively reduces foam formation in anaerobic digesters. This indirectly contributes to higher biogas production.

Refractory compounds are also produced in the process during the synergetic pretreatment in a microwave-enhanced advanced hydrogen peroxide oxidation process (MW/H_2O_2-AOP) [6]. Activated sludge treatment with H_2O_2 resulted in an 11–34% loss of total solids, COD and total biopolymers (humic acids, proteins and sugar), further enhanced by microwave irradiation resulting in solubilisation of particulate COD. However, the generated soluble organics were slower to biodegrade. Probable elevated microwave temperature could contribute to the production of refractory products. Another approach of sewage sludge pretreatment prior to anaerobic digestion is based on oxidation processes using ozone [2, 8] and hydrogen peroxide, or hydrolysis with alkaline or enzyme.

Alkaline disintegration is simple in terms of necessary equipment and operation. Alkaline sludge treatment can disrupt flocks and cells, release inner organic matters and accelerate hydrolysis. If applied as sludge pretreatment before anaerobic digestion better effects of digestion can be expected [10].

Besides this, alkaline sludge treatment can also release the water held inside flocks and cell structure, which can not be removed by conventional dewatering processes. Therefore, alkaline treatment can improve sludge dewatering ability [16]. Hydrolysis as an effect of NaOH addition depends on the added amount and reaction time. An initial period of 30 minutes is given to allow chemical reactions and penetration of the liquid of higher pH to activate sludge flocks. An example of the increase of soluble chemical oxygen demand (SCOD) is presented in Figure 1. The released SCOD is substantially higher for the initial pH of 10.

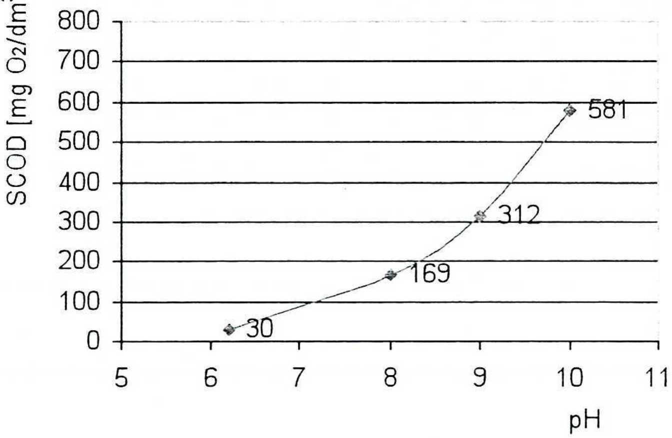

Fig. 1. Release of SCOD as an effect of alkaline addition

The effects of alkalinization are more pronounced when samples are maintained for some time under anaerobic conditions as shown in Figure 2.

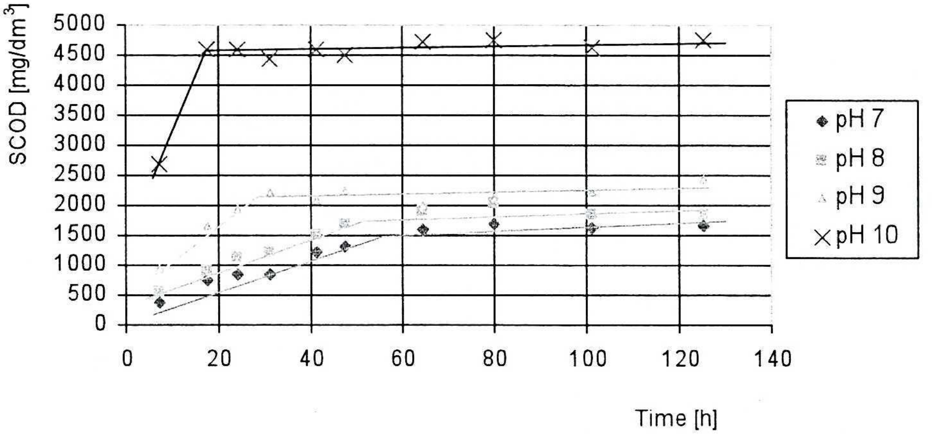

Fig. 2. Solubilization effects in anaerobic conditions for various initial pH values

The time to achieve the constant level of SCOD concentration depended on the desired alkalinization, i.e. the intended pH. The quasi constant level could be interpreted as the maximum possible to achieve degree of chemical hydrolysis. The intensity of that process depended on the initial pH. For the initial pH of 7, 8, 9 and 10, the respective solubilization time was approximately 55, 50, 30 and 15 hours (Fig. 3).

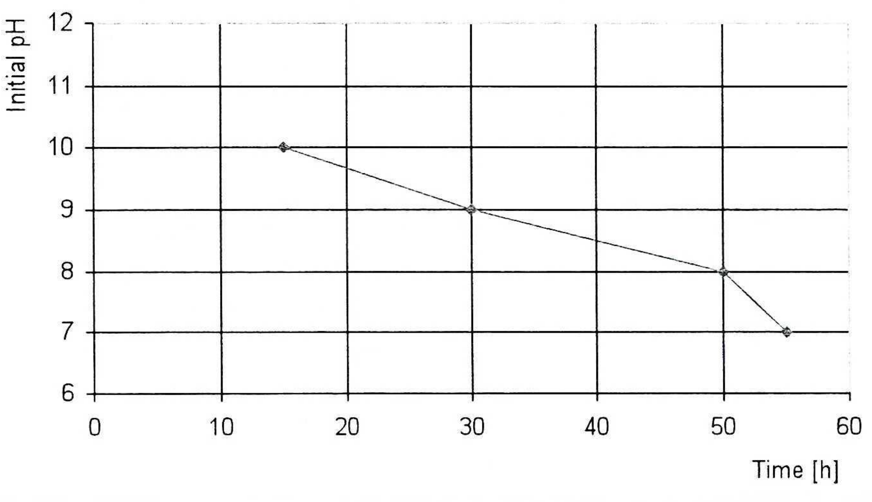

Fig. 3. Time elapsed before reaching a quasi constant solubilization effect in anaerobic conditions for different initial pH values

The effects of organic matter release SCOD can be further upgraded if combined with hydrodynamic disintegration [19, 21]. The effects of hydrodynamic disintegration of waste activated sludge, with an initial pH of 8, 9 and 10 – measured after 30 minutes of NaOH addition are given in Figure 4.

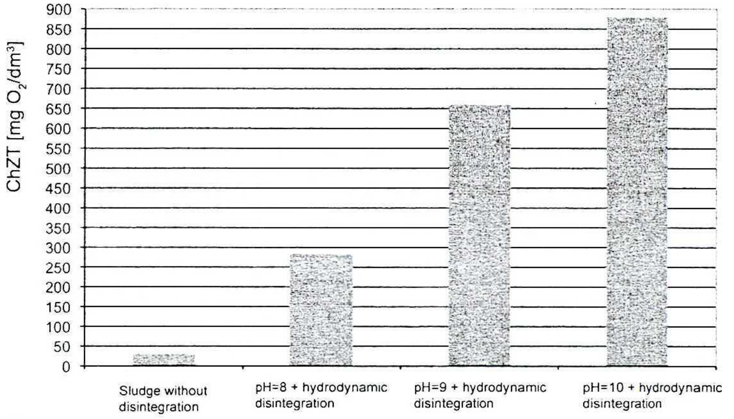

Fig. 4. Release of organic matter SCOD in the process of waste activated sludge hydrodynamic disintegration, previously spiked with NaOH

The examples discussed above show that simple activated sludge flocks dissolution techniques exist at low cost and simple additional equipment.

Probable the most promising technique of sludge disintegration prior to anaerobic digestion will be alkalinisation followed by hydrodynamic disintegration. Nevertheless, all of the aforementioned chemical, mechanical or thermal pretreatment processes have found practical full technical application; however, all have some faults either technical, or operational, or are not sufficiently cost effective.

TWO-PHASE ANAEROBIC DIGESTION

While the first phase of the process of anaerobic sludge digestion is complex organic matter hydrolysis, which, as said before, is regarded as the rate limiting step, it seems natural to exercise that step under thermophilic conditions. Obviously, the organic matter hydrolysis at higher temperature of 55°C, typical for thermophilic digestion, is more effective in comparison to the temperature of 33°C of mesophilic digestion. Unfortunately, thermophilic conditions as the first stage of anaerobic digestion result in a final product more difficult to dewater and dark brown color of the supernatant. There are no unanimous statements about the effectiveness, in terms of gas production and volatile substances reduction, of the application of thermophilic digestion as the first step or the single-stage.

The other configuration, the use of mesophilic digestion as the first step and thermophilic digestion as the second step is very seldom considered.

In order to overcome the conventional approach, a co-phase consisting of mesophilic and thermophilic processes was suggested [18]. The comparison with single stage mesophilic or thermophilic digestion has shown a much higher effect of volatile solid reduction and a sludge and supernatant quality comparable to a single stage mesophilic digestion. A 58.4% volatile solids reduction in the two stage process, that is much higher than 43.5% and 46.8% reduction respectively in the mesophilic and thermophilic single stage processes was achieved [18]. Also the soluble chemical oxygen demand (SCOD) was only about 2180 mg/dm^3 in comparison to 5240 mg/dm^3 for thermophilic digestion.

THE QUESTION OF FOAM

Filamentous bacteria such as *Microthrix parvicella*, *Nocardia amarae* or *Gordonia amarae* are responsible for activated sludge bulking and foam (scum) formation at wastewater treatment plants aiming at nutrients removal. From the very beginning of enhanced nutrients removal processes introduced in the last century, scum floating over the surface of bioreactors and secondary settling tanks raised a lot of attention. The reasons of the scum appearance and possible techniques of destruction or avoidance have been intensively investigated. The filamentous bacteria themselves do not cause foaming. They do produce biosurfactants at concentrations sufficient to generate persistent foams by reducing the rate of drainage from the foam lamellae [7].

Surprisingly, the capacity of filamentous bacteria to accumulate phosphorus has attracted very little attention. It is well documented that specific micro-organisms have the ability of excess phosphorus assimilation, which enters into composition of several macromolecules in the cell. Some bacteria including *Acinetobacter* have the ability to store phosphorus as polyphosphates in special granules (volutin granules). It has been demonstrated that the mentioned before filamentous bacteria (but not only) also accumulate phosphorus as polyphosphates in volutin granules [14]. The amount of stored phosphates is at least similar, or even higher, to that of specialized phosphorus accumulating bacteria like *Acinetobacter*. The most often present in scum filamentous bacteria *Microthrix parvicella* and *Nocardia amarae* can accumulate about 20% more phosphorus than *Acinetobacter calcoaceticus* [13].

Actinomycetes synthesize polyphosphates and poli-β-hydroxybutyrate as reserve material [13], and are able to use many nitrogen compounds, and thus have the potential to tolerate both nitrogen and phosphorus deficiencies. Phosphorus and nitrogen were found to be present in filamentous organisms in excess [12, 13] which showed that nutrients can accumulate at interfaces, thus providing a relatively nutrient reach environment (haven).

The principle of phosphorus accumulation by filamentous bacteria follows the principle of the micro-organisms present in the activated sludge flocks. Under anaerobic condition phosphates are released, and accumulated in aerobic conditions. The foam or scum floating over the surface of bioreactors, very often over all of the three sectors – anaerobic, anoxic and aerobic – does not only cause a visual negative effect but also, as it is claimed, causes serious operational troubles. There are however, properties of positive aspects in connection to the overall process of waste water treatment.

The content of phosphorus in the scum biomass expressed as g P/kg MLSS most often is found to be somewhat higher (exceptionally much higher) than that in the activated sludge. The average amount of accumulated phosphorus in the activated sludge biomass (from several large EBNR plants) that was measured in the our experiments was 26 g P/kg MLSS (2.6%), while in the scum biomass floating over the surface the accumulated phosphorus could be as high as 32 g P/kg MLSS (3.2%).

Actually the possible amounts of phosphorus to be accumulated by e.g. *Acinetobacter calcoaceticus*, or filamentous organisms such as *Nocardia amarae*, or *Microthrix* *parvicella* are very similar [13]. The higher content of phosphorus in the scum biomass in comparison to activated sludge flocks is the result of higher content of filamentous micro-organisms in the scum.

Microscopic observations show clearly the polyphosphorus volutins in the filamentous organisms, as given e.g. in Figure 5.

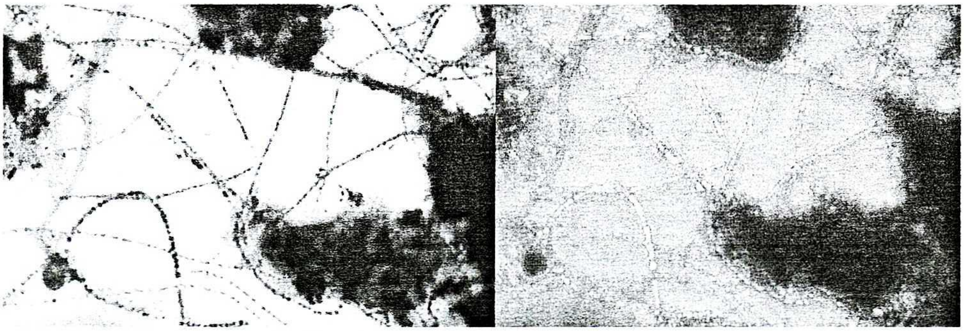

Fig. 5. Micrograph of scum showing phosphorus volutins in filamentous organisms (black or yellow dots)

Sludge or scum disintegration results in micro-organisms and associated polymeric matter dissolution, as well as release of phosphates. The photo below (Fig. 6) shows clearly partially destructed filaments and phosphorus granules thrown out. Disintegration of scum in comparison to waste activated sludge, achievement of a similar degree of organic matter and phosphates release, requires at least 50% less time and consequently the power consumption. It becomes therefore evident that the scum promises to be an effective medium for phosphorus recovery. To show the effects of disintegration (hydrodynamic disintegration) two examples are given in Figure 7.

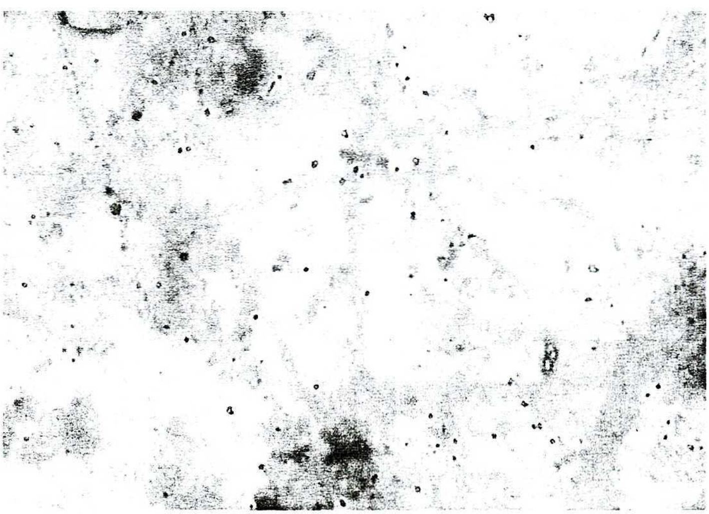

Fig. 6. Microphotos of partially disintegrated scum showing the shot out phosphorus volutins (black dots)

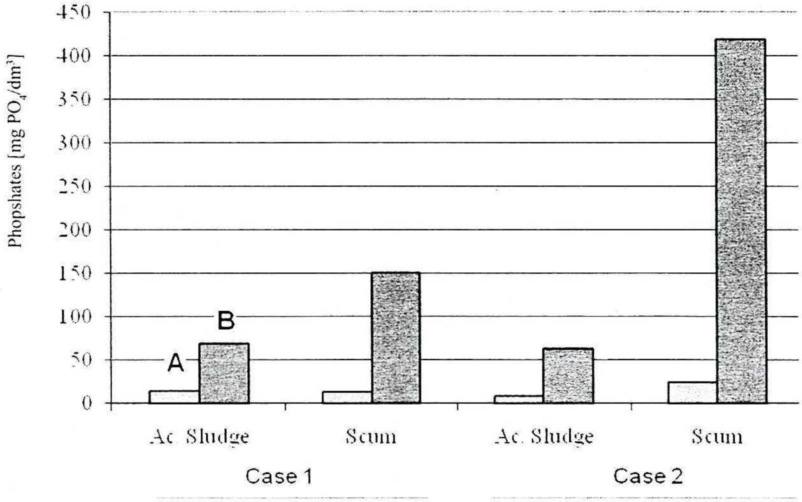

Fig. 7. Example of phosphates concentration in the liquid associated to activate sludge and scum, before (A) and after (B) disintegration

The amounts of phosphates released from waste activated sludge in the process of disintegration, were similar at all investigated EBNRP's. Seldom the amount of phosphates released, reached a level of 100 mg PO_4/dm^3. However, the amount of phosphates dissolved in the process of scum disintegration can surpass the value of 400 mg PO_4/dm^3 (approximately 130 mg P/dm^3).

Definitively the release of phosphorus is accompanied with the release of organic matter. Expressing the organic matter as dissolved (soluble) SCOD, a correlation between the released organic matter and phosphates was found. Obviously, the correlation between released SCOD and phosphates differs for different WWTP's.

In our experiments the SCOD/P ratio for WAS (Waste Activated Sludge) most often was about 18.6 g/g, while the respective ratio for scum was about 14.6 g/g. As mentioned before, the ratios can differ from case to case and the given values do not have a universal meaning. Determined here, the SCOD/P ratios correspond well to results given, e.g. by Kampas *et al.* [15]. They gave an approximate value for RAS ~ 13 g/g.

What is most interesting is the reverse ratio P/SCOD (g P/g SCOD). With the concentration increase of disintegrated biomass, there is an increase of P/SCOD ratio. Approximate values of P/SCOD are as follows:

activated sludge	0.0325	or	3.25%,
RAS	0.0538	or	5.35%,
foam	0.0685	or	6.85%.

The message from the results is that the amount of phosphorus released form the scum could be twice as high as from activated sludge taken from a bioreactor in relation to the amount of released organic matter (SCOD). That phenomenon could be explained by more effective destruction of filamentous micro-organisms. Besides the mechanical destruction of micro-organisms also the polyphosphates volutins are more easily "shot" out from the filaments.

Substantial release of phosphates by filamentous microorganisms occurs if the foam is left for some time under anaerobic conditions. Under prolonged anaerobic conditions and higher temperature of 33°C, for 15 days the determined concentration of released phosphates varied in the range from 210 up to 290 mg PO_4/dm^3. That effect is the result of biological hydrolysis. In combination with disintegration the effects of phosphates release can drastically increase.

The liquor associated to the scum contains relatively low concentrations of ammonia – up to 18 mg NH_4/dm^3. However, if left under anaerobic conditions the amount of ammonia can increase to as much as to 110 mg $N\text{-}NH_4/dm^3$. This means that in order to fulfill the struvit formula, (MAP – magnesium ammonia phosphate – $MgNH_4PO_4$) only magnesium which is in deficit has to be added [22]. It applies also to the classical process of anaerobic sludge digestion, eventually with the addition of disintegrated scum.

Recovery of phosphorus in the form of struvit is already a well established process; therefore it seems to be the most appropriate technique.

PERSPECTIVES OF SUSTAINABLE SLUDGE MANAGEMENT – AN ALTERNATIVE

Based on an extensive review of the investigated and implemented in practice sludge management options, as well as on performed investigations, an alternative approach is proposed, mainly for WAS at EBNRP's.

It has been proved that preliminary waste activated sludge disintegration has a distinctive positive effect on the effects of mesophilic anaerobic sludge digestion. On average, the effects of biogas production can increase by a factor of 1.4 (Fig. 8)

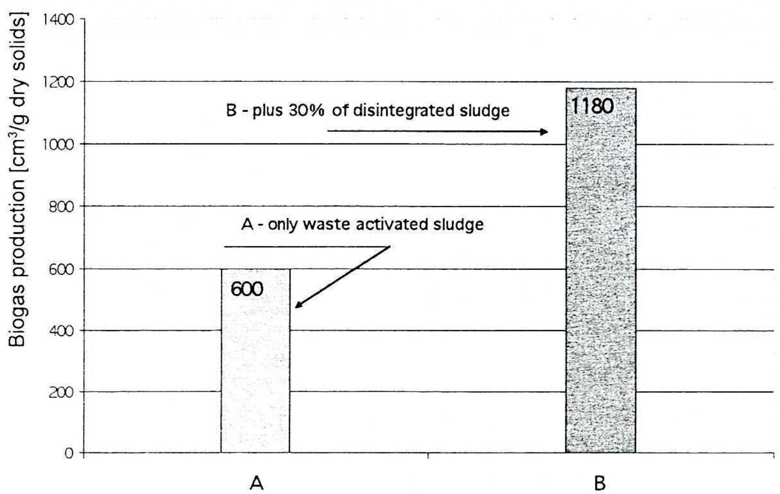

Fig. 8. Mesophilic anaerobic activated sludge digestion – biogas yield
A – only waste activated sludge, B – plus 35% of waste activated sludge preliminarily disintegrated

Disintegration of activated sludge in combination with anaerobic sludge digestion is also advantageous in terms of filamentous micro-organisms eradication being a hazard at EBNRP's. Disintegration of filamentous microorganisms in advance to anaerobic sludge digestion effectively reduces foaming in digesters, increases the biogas production, and as said before, increases the amount of phosphates released and recovered.

Having in mind a two stage anaerobic digestion process, in which the first stage would be performed at mesophilic temperatures (about 33°C), followed by thermophilic digestion, the crucial step would be volatile acids production in the first stage. Separation of the process of anaerobic digestion into two stages is widely admitted. The aim is production of higher amounts of VFA in the first stage. The optimal concentrations of VFA are obtained within a period of 3–5 days, thus the first mesophilic stage can be relatively small. Sludge lyses in advance of anaerobic digestion are advantage. As already mentioned, alkalinisation and disintegration were found to be promising alternatives [9].

The second stage of anaerobic sludge digestion, in thermophilic (55°C) conditions allows further, by up to 30%, to increase produced biogas. Simultaneously, volatile solids reduction in the order of 65% and above can be achieved.

Although it is widely admitted that recycling sewage sludge to farmland is the best practical environmental option, the threat of spreading pathogens within the environment resulted in its limited use. However, the significant benefit gained from adding organic matter and essential plant nutrients to soil for crop production and soil structural improvements has to be stressed. Much more attention is required to develop sufficiently safe sludge handling procedures, reduce the risk, and assure wider recycling of sewage sludge to the land.

Pathogen inactivation in mesophilic anaerobic digestion processes occurs however; the effects differ from case to case, and are considered to be insufficient. The inactivation process is not directly influenced by temperature (about 33°C) but is attributed to other complex factors such as microbial competition and inhibition. Additionally, thermophilic anaerobic digestion (about 55°C), as the second sludge treatment stage, decreases distinctively the risk of pathogens distribution to the farmland.

Heating further the sludge to the pasteurization level of 70°C degree, a microbial safe product can be obtained. The recommended minimum time of pasteurization is usually 30 minutes. Based on existing knowledge and carried out experiments (except for pasteurization) the below presented layout is suggested as an alterative of sludge handling (Fig. 9).

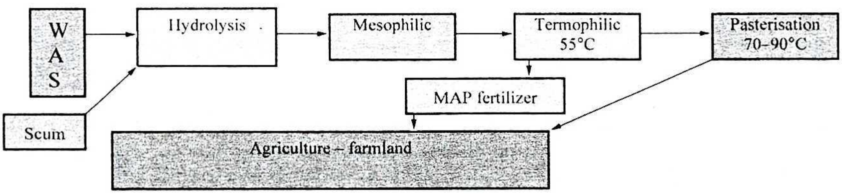

Fig. 9. Suggested alternative stream-line of complex sewage sludge handling

There are many measurable benefits, which comprise – logical stepwise temperature increase and avoiding intermittent cooling procedures. Produced sludge after thermophilic anaerobic digestion is odorless and has reasonable good dewatering conditions.

The proposed layout can be supplemented by phosphorous recovery e.g. as struvit [20] being a fertilizer.

The problem of scum (foam) has to be mentioned again, while addition of disintegrated scum to the anaerobic digester results in pronounced biogas yield (Fig. 10).

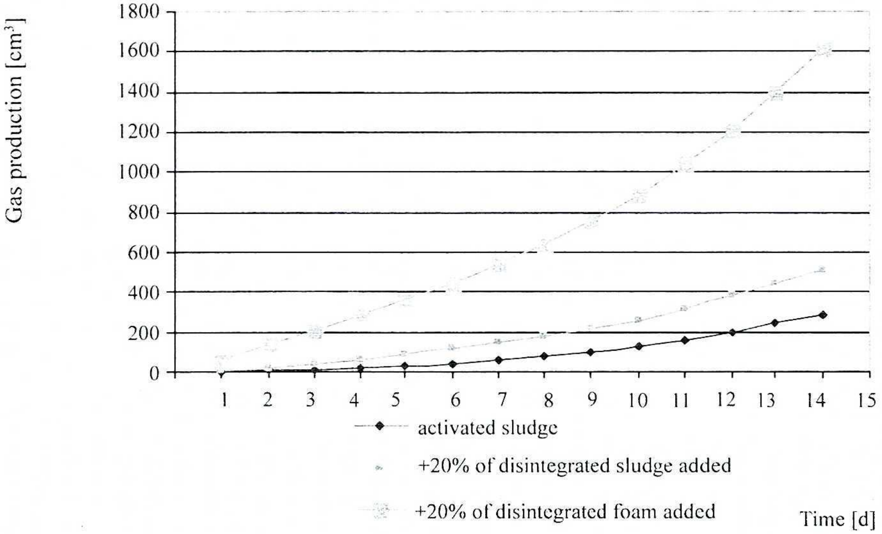

Fig. 10. Effects of disintegrated sludge or disintegrated scum addition on biogas production

The suggested above stream line of sludge management could be enriched by addition of the return stream of supernatant from sludge dewatering step of digested sludge after struvit precipitation to the sewage treatment units. Also a small part of hydrolyzed waste activated sludge can be returned to the denitrification step as a readily degradable organic substrate, including volatile fatty acids.

CONCLUSIONS

Sustainability of the environment should be based on organic matter recovery to the land. Recycling of organic matter of sewage sludge should be a priority to maintain the fertility of farm land for future food and industrial plants production. The goal of the presented alterative stream-line of processes is to demonstrate that simple, power saving or even power production and cost effective sludge handling is feasible.

Anaerobic sewage sludge digestion is an almost universally used process at medium and large waste water treatment plants for sludge handling before disposal or use as a substrate in the agriculture. New, more stringent environmental regulations as well as the introduction of nutrients removal techniques from sewage have imposed refurbishment of the anaerobic digestion process. At EBNRP's in general the only sewage sludge to be treated is waste activated sludge (WAS). Microorganisms present in WAS do not hydrolyze easily, and make the anaerobic digestion process less effective, both in terms of biogas production as well as in terms of pathogens absence in treated sludge. To overcome the obstacles an effective pre-hydrolyzes (prior to anaerobic digestion), and an effective pathogen removal process have to been introduced.

Based on carried out experiments it was proven that sludge alkalization to pH 9 with subsequent mechanical disintegration allows for a drastic reduction of the digestion time, and a distinct increase of biogas production.

A two phase anaerobic sludge digestion process is advocated, in the order, first phase methanogenic conditions (about 33°C), the second step thermophilic conditions (about 55°C). Both steps (phases), each with a hydraulic retention of 5 days, permit a good digestion sludge quality.

If there is such a requirement, to the two steps of anaerobic sludge digestion, pasteurization can be added.

Supernatant (liquor) of digested sludge thickening and/or drying, rich in phosphates should serve for magnesium ammonium phosphates (struvit) precipitation.

Appearing occasionally over bioreactors the foam formed by filamentous microorganisms which have a high ability of phosphorus accumulation, could actively participate in nutrients removal process.

Foam, if disintegrated before being supplied to anaerobic digesters, contributes to higher biogas production.

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POSTĘPOWANIE Z OSADAMI I PIANĄ W ZAAWANSOWANYCH PROCESACH BIOLOGICZNEGO OCZYSZCZANIA ŚCIEKÓW WRAZ Z USUWANIEM POŻYWEK

Procesy oczyszczania ścieków i przeróbki osadów są bardzo często prowadzone jako dwa oddzielne procesy technologiczne. Podejmując wysiłki zmierzające do zmiany tej praktyki trzeba pamiętać, że dotrzymanie standardów oczyszczania ścieków jest celem nadrzędnym a osady ściekowe są produktem ubocznym, który należy usunąć z oczyszczalni. Konsekwencje środowiskowe różnych sposobów postępowania z osadami ściekowymi są rzadko rozważane, z drugiej strony włączenie procesów przeróbki osadów w ciąg technologiczny oczyszczania ścieków może przynieść oszczędności i być przyjazne środowisku naturalnemu. W pracy, w oparciu o eksperymenty, sugeruje się możliwość ściślejszej integracji procesów oczyszczania ścieków i przeróbki osadów. Celem badań było zminimalizowanie ilości osadów, poprawienie ich jakości oraz odzysk fosforu i poprawa efektów usuwania azotu. Pojawiająca się na powierzchni bioreaktorów piana może być eliminowana w procesach przeróbki osadów.