KALMAR ECO-TECH'01
Leachate and Wastewater Treatment with High-Tech and Natural systems
KALMAR, SWEDEN, November 26-28, 2001

18 BIOREACTOR AND WETLAND COMBINATIONS

Rune Bakke
Telemark University College, Norway

ABSTRACT

Wastewater treatment plants combining bioreactors and natural processes, designed to achieve cost efficient treatment, are described and evaluated. The plants have a common general layout: an anaerobic pretreatment, an aerated bioreactor, sedimentation with sludge return and a final sub-surface flow wetland treatment. Variations in this design, adaptations to various applications, process control strategies and sludge handling are discussed. Removal efficiencies obtained varies in the range: 96-99 % BOD_7, 72-88 % COD, 92-96 % SS, 80-99 % P, 37-91% N, where more advanced control yield higher efficiency. Thermo-tolerant fecal coliform bacteria are typically removed by 99.9 %. Most of the nitrogen is removed in the bioreactors. Computer controlled aeration and sludge handling is required to obtain the high total nitrogen removal (> 80 %) Phosphorus can also be removed in the bioreactors and exported as sludge, or, more cost effectively, mainly removed in the wetland part of the plants. The cost efficiency of such treatment plants is good compared to alternative solutions.

KEYWORDS

Wastewater treatment, nutrient removal, natural treatment, biofilm, activated sludge, sustainability.

INTRODUCTION

There is a general need for robust and cost effective solutions to treat various wastewaters. Conventional solutions do not fulfill this requirement when it comes to handling nutrient and removal of toxic components. Traditional natural methods also have significant limitations, especially in colder climates. Combining bioreactors and natural processes is an approach to overcome the limitations of traditional solutions. Such integrated solutions do, however, require significant research and development, as well as some re-thinking of the design of the individual steps, to fully utilize their potentials. Some results regarding these issues, obtained the last 2 decades, is the main focus of this paper.
It is important to view the wastewater treatment solutions in both a global and a local perspective in order to get sustainable solutions. This imply that the effluent standards should be set based on local need while the technological solutions should be chosen to avoid

https://doi.org/10.15626/Eco-Tech.2001.018

negative impact on the receiving waters, the land and the atmosphere. Avoiding unnecessary energy consumptions and consumption of chemical additives is therefore always beneficial. Energy and nutrient recovery is also required to obtain sustainable solutions.
The goal of our work is to provide better and more cost effective treatment than conventional alternatives. Developing treatment concepts which can be utilized in the entire relevant size range (from single houses to several thousand persons equivalents) is an aim of this work. Six small and one slightly larger wwtp are used to illustrate the potentials of the general treatment concept presented.

METHODS

Plant Design

The treatment concept is based on literature studies, general experience, theoretical evaluations including extensive use of computer simulations and experience from various projects (Hagman et al., 1996; Sele and Nordås, 1997; Helland et al., 1997; Sele 1999; Mæhlum et al., 1998; Bakke et al., 2000; Bakke et al., 2001). The general plant design evolved to reach the goal stated above is presented in Figure 1. This design includes sludge conditioning for energy and nutrient recovery, which may be an integrated part of the treatment plant at larger plants (>2000 p.e.). Smaller plants require sludge storage facilities and sludge transport to a centralized sludge treatment plant.

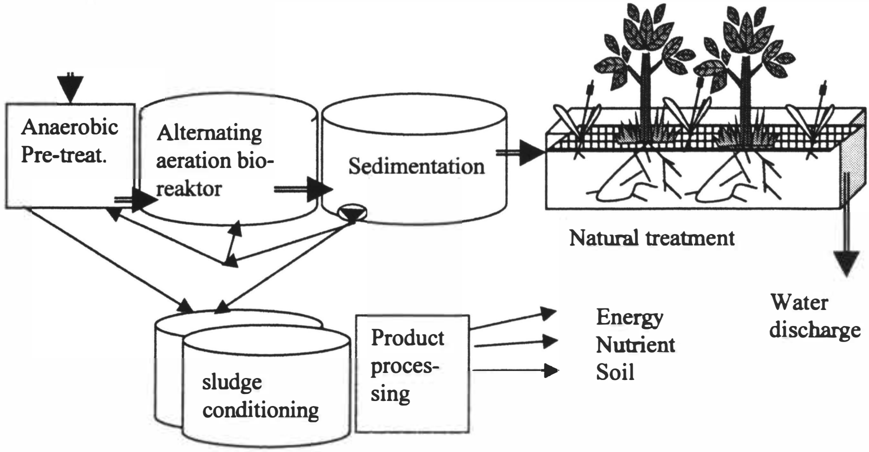

Figure 1. General wastewater treatment plant design

The anaerobic pre-treatment is a standard three compartment septic tank in the smallest plants (< 100 p.e.). Up-flow sludge blanket solutions are applied in larger plants. No pretreatment except grinding pumps (comminution) in pumping stations feeding the plants, are also tried in a few cases.

The alternating aeration bioreactors are equipped with sensors and computer control for continuous process optimization. The process control strategy, termed the HFO concept (patent pending), allow carbon and nitrogen removal in a single reactor while minimizing energy consumption (Horntvedt et al., 1998; Bakke et al., 2001). Both activated sludge and biofilm solutions are applied

Sedimentation is typically designed according to standards (e.g. Tchobanoglous and Burton, 1991). Sedimentation is in some cases closely integrated with the aerated bioreactor so that sludge flow back to the aerated reactor by gravity without additional pumping through the same channel as the wastewater flow from the bioreactor to sedimentation.

The final natural treatment process is a constructed wetland with sub-surface flow. It is designed similar to sand filters for wwt, with horizontal flow and plants.

Sludge treatment systems tested and evaluated include aerobic composting (Helland et al., 1997), "wetland conditioning" and anaerobic digestion. The smallest plants (<100 p.e.) utilize the septic tank as sludge storage (sludge from the sedimentation is returned to the septic tank). Larger plants (100-2000 p.e.) are equipped with separate sludge storage (including odor treatment). Larger plant have integrated sludge treatment.

Small plants

The smallest plants all have a combination of a 3 compartment septic tank pretreatment, aerated biofilm with sedimentation as secondary treatment and wetland tertiary treatment. The effluent from the sedimentation flows by gravity to the post treatment, while the settled sludge is pumped to the pretreatment. The biofilm reactors are either up flow packed bed reactors or fixed, submerged biofilm processes. The packed bed is aerated from the bottom with a low-pressure compressor. The filter media in the bed consist of 0.8 m of 12-16 mm gravel at the bottom and 1.55 m of 2-5 mm vulcanized clay. Reactor diameter is 1.6 m, and the total water depth about 2.5 m. The sedimentation tank diameter is 1 m, with 2 m water depth.

The post treatment is a horizontal subsurface flow wetland where the horizontal flow through the sand media is induced by different inlet and outlet levels. The filters have inlet and outlet zones with 12-22 mm gravel and treatment zones containing 0.2-1.5 mm sand; 5 m^2/p.e. with a sand depth about 0.8 m with a target hydraulic detention time of 10-15 days. The hydraulic gradient through the filters can be adjusted at the outlet. The filters are covered by about 30-50 cm of soil and plants. In some treatment plants the sand in the wetland filters was mixed with 1% (by weight) of cast iron cuttings to enhance phosphorus removal.

Treatment Processes

Larger solids are retained in anaerobic pretreatment (e.g. the septic tanks) where some of the organics are hydrolyzed. The outlet from the septic tank is treated in the aerated bio-reactors, where ammonia is nitrified during oxic and denitrified during anoxic periods, organic matter degraded and biomass produced. The biomass is separated from the wastewater by sedimentation. The sludge from the sedimentation processes is pumped to the septic tank inlet at regular, programmed intervals in the small plants. A high sludge return rate (1-2Q) to the septic tank is applied to enhance nitrate removal in some cases. In the larger plants sludge is recycled to the bio-processes and excess sludge is pumped to sludge storage and/or treatment. Larger plants under construction utilize an anaerobic reactor as an integral part of the secondary stage to obtain biological phosphorus removal. After sedimentation the water flows through the wetlands, removing more organic matter, nitrogen, phosphorus, toxins and pathogens.

Sampling and Analytical Methods

The treatment plants used as examples here are sampled every month for at least 18 months. Samples are taken both as mixed-samples over a 24-hour period and as grab-samples. Most samples are mixed samples taken with automatic samplers. The flow through the treatment plants are measured continuously. The parameters reported are analyzed in approved Norwegian laboratories according to Norwegian standard methods.

RESULTS

Data reported are based on measurements of samples from the inlet to the bioreactors (after pretreatment); from the sedimentation tank outlet; and from the constructed wetland outlets, during test period of 1.5-3 years. The total efficiency of the plants is, therefore, somewhat underestimated, as the treatment in the pretreatment is disregarded.

Small Plants

Loading

Average hydraulic loading and inlet concentrations in the 6 treatment plants presented here, P1-P6, during the test period are summarized in Table 1. The hydraulic loading, Q, varied between 200 and 4200 l/d, at an average around 1000 l/d (1 m^3/d). The mass loading was used to calculate person equivalent, p.e., loading. The hydraulic loading on a person equivalent basis was on average <150 l/p.e./day. Wash-water from milking machines (dairy farming) was treated along with domestic sewage in plants 3 and 4 causing the mass loading on P3&4 to be significantly higher than the rest.

	P1	P2	P3	P4	P5	P6
Q (l/d)	1022	1076	600	1254	1330	1570
BOD_7 (mg/l)	198	300	585	391	148	167
COD (mg/l)	322	439	857	576	254	316
Tot-N (mg/l)	69	84	147	66	112	79
NH_4 (mg/l)	61	66	123	52	89	70
Tot-P (mg/l)	8	9	16.2	9	10	9
SS (mg/l)	56	80	155	101	54	37
p.e.	7	10	6.5	7.5	14	7
Q/p.e. (l/d/p.e)	140	100	85	150	95	224

TABLE 1. Hydraulic and mass loading.

Removal Efficiency

The removal of pollutants, measured as g/d, through the bioreactor and sedimentation parts of the plants, are presented as % reduction compared to inlet concentrations in Table 2a (number of samples for each value; 14<n<23). The results are presented as the average of pairs of plants of similar design/operation. Standard deviation for the samples are also presented.

Total % reduction of the various pollutants, measured as g/d, through the bioreactors, sedimentation and wetland (number of samples for each value; 14<n<23), is presented in Table 2b. The results are presented as the average of the same pairs of plants of similar design as above.

All plants remove >96% BOD, with consistently 99% removal in P3&4 plants (effluent concentrations < 4 mg/liter). The removal in the reactor part of the plants vary more, with 83% in P5, while P3&4 remove 99%. P3&4 also remove COD more efficiently (90%) and consistently compared to P1&2, which remove 78%, while P5&6 remove 62%. All COD removal in P1-4 is obtained in the reactor part while approx. 10% of the COD removal in plants P5&6 occur in the constructed wetlands.

a.	P1&2		P3&4		P5&6	
	%	SD	%	SD	%	SD
BOD_7	95.5	1.5	99	0	87.5	4.5
COD	78.5	6.5	90.5	0.5	62.5	3.5
Tot-N	29	5	68	0	40	6
NH_4	74.5	12.5	93	1	72	6
Tot-P	39	17	36.5	2.5	7	11
SS	78.5	6.5	77.5	3.5	29	7

b.	P1&2		P3&4		P5&6	
	%	SD	%	SD	%	SD
BOD_7	97.5	1.5	98.5	0.5	97.5	0.5
COD	80.5	7.5	87.5	0.5	73	1
Tot-N	38	1	83.5	2.5	61	3
NH_4	81.5	0.5	94	2	75.5	8.5
Tot-P	86.5	6.5	96.5	2.5	90	4
SS	94.5	1.5	95	0	93	1

TABLE 2. a. Removal efficiency (%) and standard deviation (SD) of pollutants in the bioreactor and sedimentation. b. Removal efficiency (%) and standard deviation (SD) of pollutants in the total treatment system

Total nitrogen removal varied from >80% in P3&4, with the more advanced process control, to less than 40% in P1&2. Most of the nitrogen was removed in the reactor part of the processes and 18-35% in the wetlands. A removal efficiency of 75-94% for ammonia was measured, of which just a few percent occurred in the wetlands. The control of the aeration equipment greatly affected the nitrogen removal rates.

Total phosphorous removal was consistently well above 80%, of which 92, 62 and 55% occurred in the wetlands in P5&6, P3&4 and P1&2, respectively. A slight reduction with time in P removal in the wetlands is observed. Suspended solids, SS, removal of 93-95% is measured in all plants, of which >80% occurred in the reactor parts of P1-4 while most SS removal occurred in the wetlands in P5&6.

Around 99.9% of the thermo-tolerant coliform organisms (fecal coliform; FC) were typically removed in these plants, yielding an average effluent quality close to the Norwegian "recreational (swimming) water quality standard" of maximum 100 FC/100ml.

Cost

Bakke et al. (2000) found that the average operation and capital cost was about US $130/p.e./y, which is at the same level as the cost of infiltration and as the larger wwtp operated by the municipalities in the region. It is therefore more cost effective to build a separate treatment plant when there is some distance to the nearest sewer. Sand filters and commercially available pre-fabricated treatment systems are more expensive alternatives with lower effluent quality (Hagman et al., 1997; Dahle et al., 1998; Leirset,1996).

Medium Size Plants

A wastewater and sludge treatment plant, designed to solve local pollution problems in a rural community, in operation since 1994, is used as example of a slightly larger plant with integrated sludge handling. Detailed results from the first 2 years of operation are reported by Helland et al. (1997). Pretreatment is limited to comminution. The wastewater is treated in a biofilm reactor with sedimentation, followed by a pond and wetland concept. Sludge produced in the wastewater treatment and in septic tanks throughout the municipality is treated in a three stage aerobic digestion process designed for nutrient recovery.

Loading

Wastewater, at an average hydraulic loading rate of 22 m^3/d, is fed the aerated reactor (53 m^3) through grinder pumps (comminution), with no other pre-treatment (no screening nor grit removal). Produced sludge is pumped to an aerated digester from the sedimentation and sludge collected from septic tanks in the region, enters the sludge treatment process at the first (a pre-treatment and inlet storage tank) of a three stage aerated reactor configuration. The plant treats wastewater from about 300 p.e. and sludge from about 3500 p.e.

Treatment results

Total phosphorus is reduced from 4 to 2 mg/l in the bioreactor and sedimentation, and further to 0.4 mg/l in the wetland (90 % removal). Total nitrogen is reduced from 45 to 15 mg/l in the bioreactor and sedimentation, and further to 4 mg/l in the wetland (91 % removal). Suspended solids are also reduced by $\approx$90 % through the plant.

The aerobically digested sludge is used as agricultural fertilizer without dewatering. Most thermo-tolerant coliform organisms (fecal coliform; FC) were removed, yielding an average quality slightly above 100 FC/100ml. The product is quite stable and odor free.

Cost

The annual operational cost is about US $ 20/p.e./y. The average operation and capital cost is about US $110/p.e./y, which is slightly below the cost of the smallest plants. The treatment cost per m^3 of sludge is about US $ 30/p.e./y, not accounting the capital cost.

DISCUSSION

Anaerobic pretreatment

Anaerobic pretreatment designed as sludge blanket processes is included in then larger plants under construction. The purpose of this design is to remove particles which may serve as energy source in the sludge treatment and at the same time produce volatile fatty acids for biological phosphorus removal downstream. One project in the planning stage will expand on the possibilities of such solutions including organic household (food) waste through kitchen sink grinders. The potential of gains of such solutions are significant, given that the sewer lines are of high quality.

An anaerobic reactor is also included as an integral part of the secondary stage in plants under construction to enhance biological phosphorus removal. This allow for compact biological nutrient removal in a two stage reactor configuration (se below), which is suitable for cost effective new plants, as well as upgrades of traditional activated sludge plants. Such solutions enhance our ability to recover non-renewable nutrients for agriculture. It also reduce the load on the wetlands, allowing more compact tertiary treatment and longer "life expectancy".

Aeration strategies

Hao and Huang (1996) presented an evaluation of temporal versus spatial separation of nitrification and denitrification and concluded that the process efficiency can be higher in spatially separated processes. They still recommended alternating aeration because of lower cost and complexity and most of all because of better possibilities for process control. The ability to handle transient conditions is particularly important since most wastewater treatment plants are exposed to unpredictable, strong and frequent load changes (concentration and volumetric changes). It has been demonstrated in our work that the process efficiency in oscillating processes can be improved to match that of optimised spatially separated processes at steady state (Bakke et al., 2001). Limited acceptance/experience in the market, therefore, seem to be the main obstacle at present for the proliferation of oscillating processes for wastewater treatment. A typical oxygen curve and some definitions are presented in Figure 2. It is concluded that single stage nitrogen removal is achievable and "BNP" can be obtained in a two stage activated sludge process using high frequency intermittent aeration.

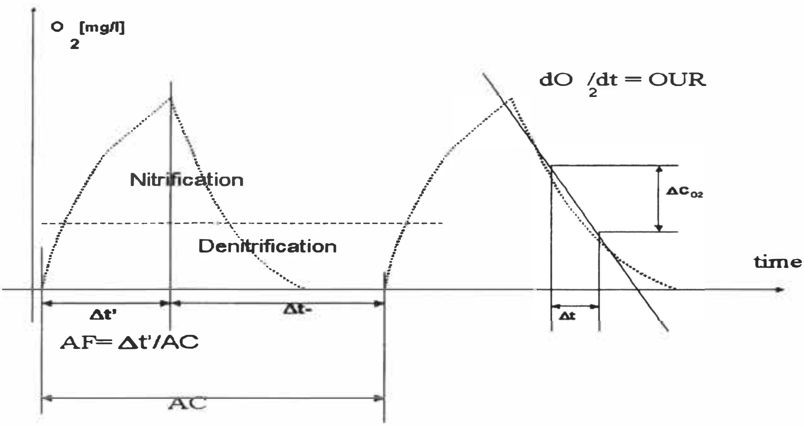

Figure 2. A typical bulk liquid oxygen profile, including definition of aeration fraction (AF), aeration cycle (AC) and oxygen utilization rate (OUR).

Sludge treatment

It is determined that anaerobic sludge digestion with biogas utilization as a renewable energy source and nutrient recovery for plant fertilization is the most sustainable solution. It may not always be economically favorable, however, especially when treating sludge from less than 10k p.e. Improved anaerobic process control to improve cost effectiveness is, therefore, top priority in our R&D.

CONCLUSION

The general treatment concept presented, combining intelligently controlled bioreactors with wetlands, has the flexibility to sustainably handle large and small wastewater flows at competitive costs. Advanced process control is a prerequisite to maintain high efficiency, as well as integrated sludge treatment with energy and nutrient recovery.

ACKNOWLEDGEMENTS

The solutions presented are made possible through support from the national departments of Environment (MD&SFT) and Business development (SND), the national science foundation (NFR), local governments and private companies.

REFERENCES

1. Bakke R., Amrani S., and Lie B. (2001). Biological nitrogen removal from wastewater; simulations and control strategies. Proceedings. 42nd Conference on Simulation and Modeling; SIMS 2001. Porsgrunn. Norway.

2. Bakke R., Hagman E., Ollestad P.H., Sele K. (2000). Nutrient removal in combined bioreactors and wetland systems in Norway. J. Env. Sci. & Health. (in press).

3. Dahle, Ø.D., Hongseth, N. and Klempe, H., (1996). Aksjon Jærvassdrag. *Vurdering av sandfilteranlegg.* AJV-report 13/96.

4. Hagman, E., Ollestad, P.H. og Bakke, R. (1997). Løsninger for rensing av avløp i spredt bebyggelse: Kostnadsanalyse. I: *Kommunalteknikk nr. 5.*

5. Hagman E., P.H. Ollestad and Bakke, R. (1996). Utforming, effekter og modellering av renseparker. Vann, 2, pp. 306-315.

6. Helland A.I, Kommedal, R. and Bakke, R., A wastewater and sludge treatment process integrating biofilms, wetlands and aerobic sludge digestion for nutrient recovery. Proceedings from Nordisk konferens; Kväverening och biologisk fosforrening (1997).

7. Horntvedt, B., Rambekk, M., Bakke, R., Oscillating conditions to influence the compositions of mixed biological cultures, Wat. Sci. & Tech., 37, No 4-5, (1998), pp. 259e- 262.

8. Hao, O.J. and Huang, J. (1996) Alternating aerobic-anoxic process for nitrogen removal: Process evaluation, Water Env. Res., 68, No 1, pp. 83-93.

9. Leirset N.G., *Utslipp fra spredt bebyggelse - opprydding.* Sluttrapport. Inderøy kommune, (1996).

10. Mæhlum, T., Jenssen, P.D. and Warner, W.S. (1995) Cold-climate constructed wetlands, Wat. Sci. & Tech., 32, No 3, pp. 95-101.

11. Mæhlum, T. and Jenssen, P.D. (1998) Constructed wetlands for wastewater treatment in Norway, Published in: J. Vymazal, H. Brix, P.F. Cooper, M.B. Green and R. Haberl (Eds.), Constructed wetlands for wastewater treatment in Europe, Backuys Publishers, Leiden, The Netherlands, pp. 207-216.

12. Sele, K and Nordås, S.O. (1997) *Konstruerte våtmarker - Vurdering av dimensjoneringskriterier for hydraulisk kapasitet.* Hovedoppgave ved Norges Landbrukshøgskole - Institutt for Tekniske Fag.

13. Sele, K. (1999) Aksjon Jærvassdrag v/ Fylkesmannen i Rogaland, Landbruksavdelingen. *Utprøving av kloakkløsninger for spredt bebyggelse.* AJV-rapport nr. 29/99.

14. Tchobanoglous G. and Burton F.L. (1991) Wastewater engineering; Treatment, disposal and reuse. 3.ed. (Metcalf & Eddy) McGraw-Hill.