

The influence of wastewater characteristics on choice of wastewater treatment method

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Introduction

In advanced wastewater treatment the effluent standards are currently aiming at removing particles (suspended solids), organic matter (BOD, COD, TOC) and nutrients (nitrogen and phosphorous). Various treatment methods may be used, physical, chemical and biological as well as combinations of these. Among these main treatment methods, there are many reactor and process alternatives. Traditionally the choice of treatment method has mainly been based on the effluent standard set in individual cases as well as practical experience with the various methods. This has resulted in the fact that some methods and processes are more favoured in some places than in others. In UK for instance, biological treatment has been favoured even in cases where chemical treatment for phosphorous removal (in combination with biological treatment) might have been the right choice from the receiving water point of view. In Norway, on the other hand, the good experience with chemical treatment for phosphorous removal has led to the use of chemical treatment even in cases where phosphorous is not the key element from the receiving water point of view.

After the introduction of biological nitrogen and phosphorous removal this picture has changed somewhat but we can still see tendencies towards "preferred" solutions in the Nordic countries. Now it is being realised, however, that in addition to effluent standard and traditional experience, one has to take account of the characteristics of the wastewater in order to arrive at the most economical solution. In this paper wastewater characteristics will be discussed in this perspective.

Wastewater characteristics

There are several ways of characterising wastewater :

1. According to bulk parameters, such as suspended matter, organic matter, nutrients, bacteria etc
2. According to the state, such as soluble, colloidal, particulate, gaseous etc
3. According to its treat-ability such as biodegradability, ability to separate etc

Normally wastewater treatment plant owners restrict themselves to characterising in terms of bulk parameters since this is the way the effluent standards are given, but also because other characterisation methods may be costly and difficult to perform. Bulk parameters do not, however, give sufficient information with respect to optimal selection of treatment method/process and optimisation of operation.

In this paper it will be focused much on the need and benefit to know and understand wastewater characteristics in terms of the state in which the various compounds are present, that is if they are present as soluble, colloidal or particulate matter. This is knowledge can be acquired quite easily and cheaply. Nevertheless it tells a lot about the treat-ability of the wastewater and therefore also about the most economical choice of method with respect to both investment and operation. The various compounds may be present in wastewater as soluble ($d < 1\text{ nm}$), colloidal ($1\text{ nm} < d < 1\text{ }\mu\text{m}$) or particulate matter ($d > 1\text{ }\mu\text{m}$). Suspended matter, normally determined by filtering through a $1\text{ }\mu\text{m}$ filter, contains the particulate but not the colloidal matter. It has been demonstrated (Levine et al, 1985) that most of the mass in colloids will be included when a $0,1\text{ }\mu\text{m}$ filter is used.

Especially since nitrogen removal came into operation, the need to characterise the wastewater according to biodegradability has become evident and even more so since biological phosphorous removal has come into use. Various characterisation techniques have been introduced such as oxygen uptake rate (OUR), nitrogen uptake rate (NUR) various C/N-ratios etc. Specific analyses such as VFA (volatile fatty acids) have also been used as well as various interpretations of COD-analyses, such as BSCOD (biodegradable, soluble COD). The state in which especially organic matter is present in the wastewater is very important and therefore characterisation with respect to particulate fractions may shed some light also on biodegradability.

A survey on wastewater characteristics with special emphasis on particulate content

There has not been any surveys carried out in order to analyse the presence of particulate matter in Scandinavia, but experiences from Norway and Sweden have indicated that the particulate fraction may be even higher in some Scandinavian plants than elsewhere. It was, therefore, decided to try to evaluate the situation in the Scandinavian countries. Unfortunately it was only possible to collect relevant data from only one Danish plant. The analysis will concentrate, therefore on data from Sweden, Finland and Norway. It is mostly data from those plants that have to remove nitrogen that are included.

As expected, it was not standard procedure to analyse on filtered samples. Those plants that had carried out such analyses either in connection with special projects or as a routine, normally used a standard $1\text{ }\mu\text{m}$ filter. In some cases the data are based on yearly averages and in some cases on single day samples. The main issue has been to evaluate to what degree organic matter (BOD and COD) and nutrients (P and N) are connected to suspended matter in Scandinavian wastewater.

One will see that there are great variations in wastewater characteristics from plant to plant and from country to country. Based on the data collected, it will generally be seen that the Norwegian wastewater was found to be much more dilute than that in both Sweden and Finland. Especially the Finnish wastewater was found to be quite concentrated indicating more comprehensive use of separate sewerage systems in Finland.

Organic matter

In table 1 are summarised the data reported on suspended solids and organic matter.

Table 1 Average values on organic matter in raw wastewater from Scandianvian plants

Country	N ¹	SS	COD	COD _f	Fract. COD _{ss}	BOD	BOF _f	Fraction BOD _{ss}	BOD/COD	
									Tot	Filtr
Sweden	17	243 ±87	477 ±123	157 ±79	0,68 ±0,10	171 ±72	63 ±47	0,66 ±0,12	0,32 ±0,12	0,38 ±0,10
Norway	12	143 ±39	233 ±69	81 ±30	0,66 ±0,11	113 ±28	33 ±9	0,71 ±0,11	0,48 ±0,21	0,48 ±0,17
Finland	7	378 ±144	559 ±161	164 ±22	0,71 ±0,06	266 ±78	81 ±27	0,71 ±0,06	0,46 ±0,08	0,43 ±0,05

¹Number of plants included

The data-base is better for COD than for BOD. Nevertheless it is quite remarkable that even though the concentrations of organic matter is vastly different from one plant to the other, and from one country to the other, the fractions of suspended COD and BOD are generally high and quite similar in the three countries. Table 1 indicates that one can expect that the suspended organic matter (both as COD and BOD) in the wastewater of these countries is close to 70 % of the total. And this does not include the colloidal fraction that can be estimated to be in the range of 10-15 %. This means that only a fraction of 15-20 % of the total COD is truly soluble.

Figure 1 demonstrates that there are big differences, but that the particulate fraction does not seem to be dependent on the COD-concentration of the wastewater or country. In many cases the fraction of suspended COD is higher than 75 %, in some even higher than 80 %. It can be noticed in figure 1 that the Norwegian wastewater seem to have generally a lower total COD- and BOD-concentration than the Swedish and especially the Finnish wastewater, even though the fraction of soluble COD seem to be about the same.

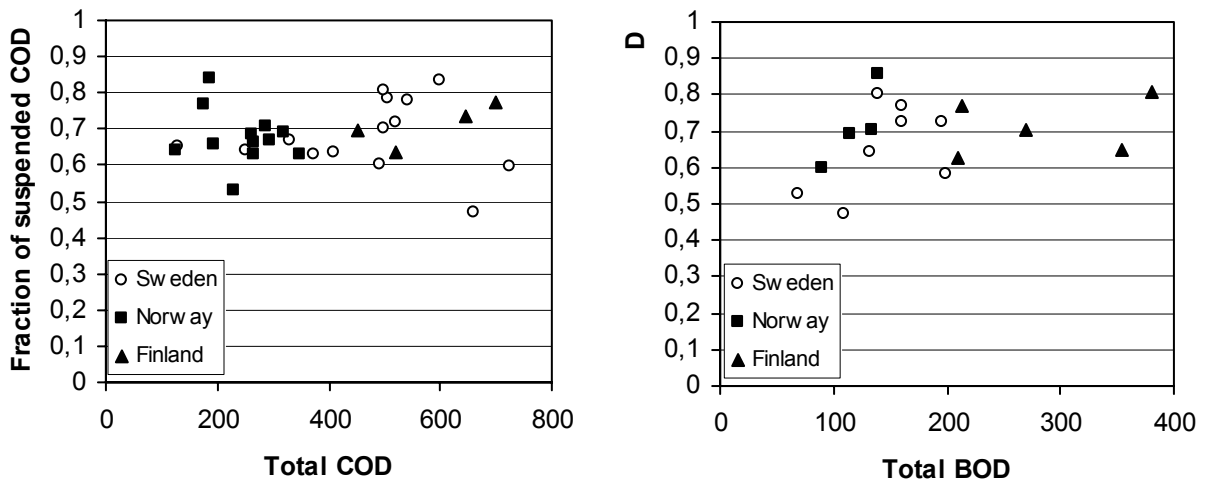


Fig 1 Fraction of suspended COD and BOD versus total COD and BOD

How large the fraction of biodegradable organic matter is in a given case, is dependent upon; (1) Origin of the wastewater - for instance influence of food industry wastewater, (2) Influence of leakage water - storm water and infiltration water and (3) Characteristics of sewer system.

It seems more and more clear that processes taking place in the sewer network play an important role. These processes may be physical (settling), chemical (precipitation) and biological (biodegradation). Of special importance with respect to organic matter are biodegradation processes and therefore availability of oxygen in the sewer system. If the wastewater carries an ample concentration of oxygen, aerobic biodegradation will take place in biofilms and in bioflocs. The most easily biodegradable matter will rapidly be converted into bacterial cells, i.e. into particulate, less biodegradable matter. On the contrary, if anaerobic conditions prevail in the sewer system, biodegradation of soluble organic matter is very slow. Hydrolysis of the particulate fraction of the organic matter may be significant, however, and result in an increase in the soluble fraction and a decrease in the particulate fraction. This may explain some of the regional differences. In Norway, for instance, there are many wastewater systems that carry oxygen-rich wastewater (caused by high flow speed, many pumping stations, large water surface-to-volume ratio etc). In most of the Norwegian plants reported, the soluble COD-concentration is well below 100 mg/l. It is experienced that the non-biodegradable soluble COD in these kind of waters is in the order of 30-40 mg/l. This may vary from country to country, but different investigations in the three countries (Mattsson, 1997), (Carlsson et al, 1997), (Jeppson, 1997), (Rautiainen, 1995) indicate that this is a level of non biodegradable COD that is typical in Scandinavia.

When the level of soluble COD is low in the first place and the level of non-biodegradable COD seem to be at a certain level (30-40 mg COD/l), the level of biodegradable COD can be expected to be particularly low in Norway as compared to Sweden and particularly Finland. In figure 2 the "BSCOD"-concentration for the different plants is plotted, assuming that the non-biodegradable soluble COD-concentration is 35 mg/l in all cases. The average BSCOD-levels calculated this way is $122,4 \pm 79,2$ for the Swedish plants, $129,3 \pm 22,0$ for the Finnish plants and only $46,7 \pm 28,3$ for the Norwegian plants. There are large variations, especially at higher COD-concentrations, where the assumption about a constant concentration of non-biodegradable COD may not hold. The figure demonstrates well, however, that the concentration of biodegradable, soluble COD in the Norwegian wastewater can be expected to be very low, in some instances close to zero.

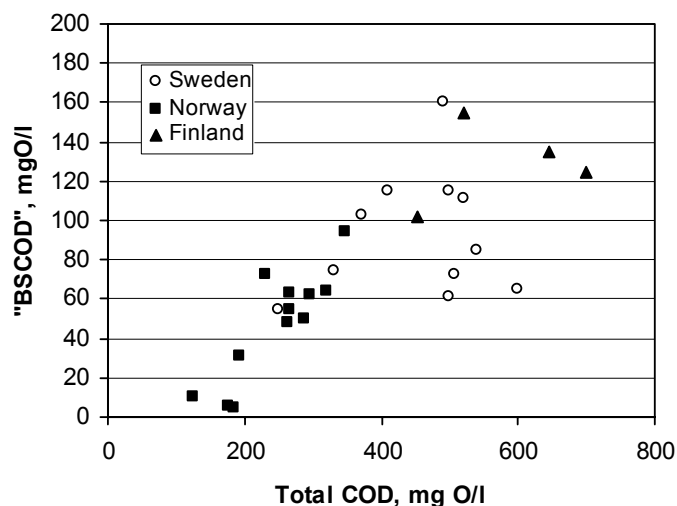


Figure 2 "BSCOD"-concentration versus total COD-concentration

It is obvious that also some of the suspended organic matter is biodegradable. It is probably more slowly biodegradable, however, since hydrolysis has to be involved in order to this organic matter to be biodegraded. We may analyse this matter by looking at the BOD/COD-ratio (see figure 3). There were, however, fewer BOD-data than COD-data and therefore the analysis becomes a bit uncertain.

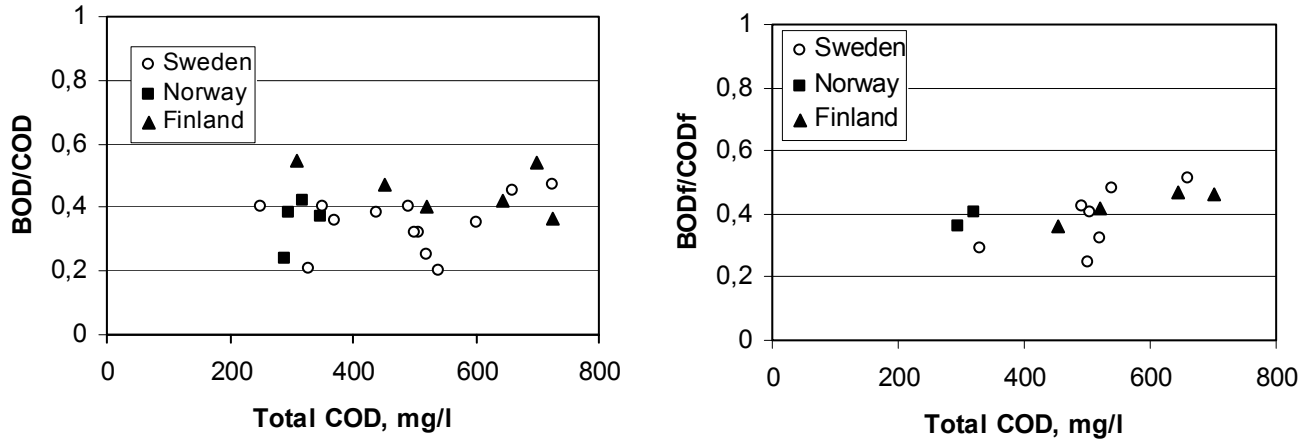


Figure 3 Ratio BOD/COD and BOD_f/COD_f versus total COD

Again we can see that the variation between the different countries is not so great and that the fraction is around 0,4 in both cases. There is a tendency, however, that the fraction of biodegradable organic matter to that of total organic matter increases with increasing total COD. This is particularly evident in the filtered samples. This is also reasonable, since it may be expected that the amount of organic matter that is biodegraded in the network is relatively independent upon the concentration of biodegradable COD as long as there is no limitation with respect to the presence of biodegradable matter.

Nitrogen and phosphorus

Nitrogen appears in wastewater mainly as ammonium and therefore the particulate fraction of nitrogen is quite low. In the survey, some plant owners have reported data on tot N on filtered samples, but most reported data on NH₄-N and NO₃-N (or only NH₄-N) in addition to tot N. It was demonstrated in a survey of Norwegian plants (Østerhus, 1991)(Ødegaard, 1992), that the organic N primarily exist on suspended form (see table 2).

Table 2 Nitrogen in wastewater from 10 Norwegian, chemical plants (Ødegaard, 1992)

Parameter	Inlet		Outlet	
	Average	Variation range	Average	Variation range
Tot N	24,8	14,6 - 45,0	20,9	11,8 - 34,8
Tot N _f	19,6	11,6 - 45,0	20,4	11,7 - 32,6
NH ₄ -N	19,1	9,1 - 45,0	18,3	6,5 - 32,6
NO ₃ -N	0,1	0 - 0,2	0,1	0 - 0,2
NO ₂ -N	0,3	0 - 1,4	0,6	0 - 2,4

It can be seen that the particulate fraction of the tot N was around 20 %, and that the filtered Tot N was about equal to the inorganic N. Consequently the organic N was mainly on particulate form. This can also be seen from the fact that the amount of N left after coagulation was very close to the sum of the inorganic N. In table 3 the results of the survey of the Scandinavian plants are shown with respect to nitrogen as well as phosphorus.

Table 3 Average values on N and P in raw wastewater from Scandinavian plants

Country	N	Tot N	NH ₄ -N	F-N _{ss} ¹	Tot P	PO ₄ -P	F-P _{ss} ²
Sweden	17	33,1	24,4	0,28	6,14	3,26	0,49
		+8,1	+7,6	+0,13	+1,65	+1,42	+0,15
Norway	12	22,0	13,7	0,29	3,00	1,10	0,65
		+6,2	+4,2	+0,08	+1,12	+0,62	+0,09
Finland	7	43,8	28,7	0,33	7,47	3,29	0,56
		+10,4	+7,6	+0,07	+1,34	+1,36	+0,19

¹ Based on the assumption that the organic N is suspended

² Based on the assumption that the soluble P is equal to soluble PO₄-P

As it is shown in figure 4, the suspended fraction of tot N varies between 0,2 and 0,5, but is in most cases around 30 %. It seems to decrease a bit with increasing tot N concentration. Generally it seems from the data that the plants with a higher fraction of soluble COD had a lower fraction of particulate N. This seems reasonable, since the particulate N to a large extent is organically N bound in biomass. In oxygen-rich systems with considerable biodegradation, inorganic, soluble N (NH₄-N) is used in the assimilation process producing biomass, i.e. particulate, organic N.

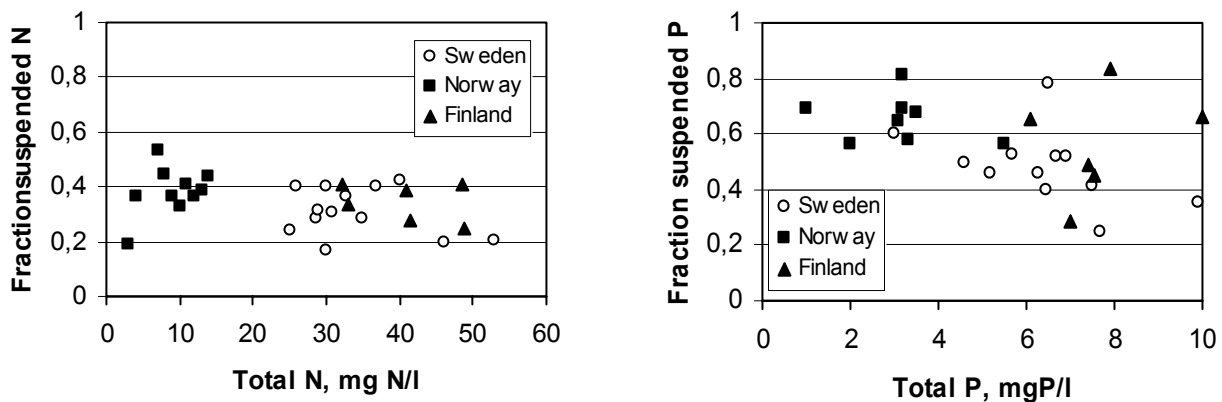


Figure 4 Fraction of N and P on suspended form

In the survey, some plant owners gave data for filtered tot P and some only on PO₄-P. The difference was not great. However, filtered tot P is on average somewhat higher than PO₄-P. There were large variations from plant to plant with respect to the particulate fraction of phosphorous (30-80 %). This may be caused by the fact that the sludge water may influence in some cases on inlet concentrations since the inlet sampling point in some cases may be downstream the introduction point of the sludge water. It was a bit surprising, however, that in most of the plants the fraction of particulate P was higher than 50 %. Again, it is the plants with a low fraction of soluble COD, that has a high fraction of particulate P. As mentioned for nitrogen, this indicates again that a considerable fraction of the particulate P is in fact present in biomass.

C/N-ratios and C/P-ratios

In table 4 are given calculated C/N- and C/P-ratios. The C/N-ratio is often taken as an indication of the availability of carbon source for pre-denitrification. One has to remember, however, that it is the biodegradable organic matter that counts, and that particulate nitrogen may be hydrolysed during the process (extent depending on which process). The C/N-ratios that tell us most, therefore, is probably the BOD/Tot N-ratio or the BSCOD/Tot N-ratio.

Table 4 Average values calculated C/N- and C/P-ratios from Scandinavian plants

Country	N	COD/ TN	COD _f / NH ₄ -N	BOD/ TN	BOD _f / NH ₄ -N	BSCOD/ Tot N	BSCOD/ NH ₄ -N	COD/ TP	COD _f / PO ₄ -P
Sweden	17	14,7 ±3,3	7,1 ±4,2	5,2 ±2,1	2,6 ±1,0	3,8 ±2,6	5,5 ±4,0	79,5 ±7,2	55,5 ±23,9
Norway	12	11,5 ±1,4	6,3 ±1,4	5,2 ±2,3	2,2 ±0,7	2,1 ±0,8	3,3 ±1,3	86,7 ±24,9	93,2 ±48,3
Finland	7	13,5 ±5,0	5,3 ±1,8	6,1 ±1,4	3,3 ±1,3	2,8 ±0,9	4,2 ±1,6	78,2 ±29,3	75,4 ±52,1

It is interesting to note that even if there are great variations between the C/N-ratios when comparing the three countries, the differences are smaller than one could expect, even though the Norwegian waters generally seem to be less suitable for pre-denitrification than the ones in Swedish and Finland. Based on the COD/Tot N-ratio alone one might draw the conclusion that the available carbon source is more than sufficient for pre-denitrification in most cases. When considering the BSCOD/Tot N-ratio, however, one may fear that the available carbon source is insufficient in many cases (see figure 4), especially when there is not time available for hydrolysis (as in some biofilm processes). One has to remember, however, the carbon source that will be needed for oxygen assimilation. Especially in the Norwegian wastewater the oxygen concentration in the inlet water is normally high, making this wastewater even more unfavourable for pre-denitrification.

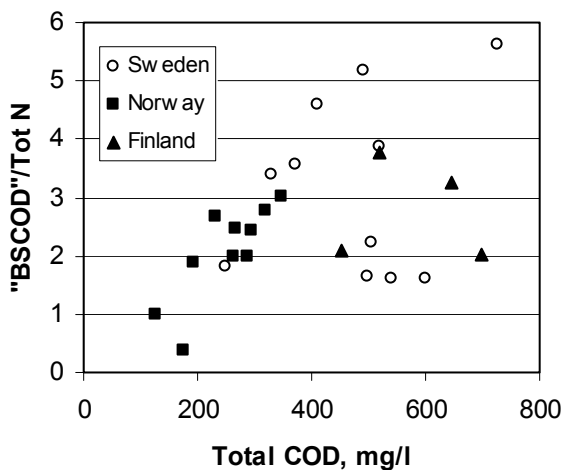


Figure 5 "BSCOD"/TotN versus COD concentration

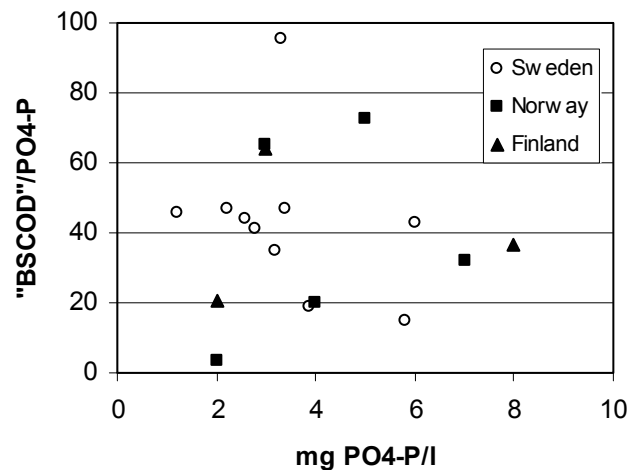


Figure 6 "BSCOD"/PO₄-P ratio versus PO₄-P concentration

It is difficult to evaluate the C/P-ratios since biological phosphorous removal is totally dependent upon the availability of readily biodegradable organic matter (i.e. VFA). The C/P-ratios given in table 4 do not tell much, therefore. In figure 6, the "BSCOD"/PO₄-ratio is plotted against the PO₄-P concentration. This ratio is probably the one that tells most. It is obviously great differences among the plants with respect to suitability for bio-P removal.

Influence of wastewater characteristics on optimal selection and operation of treatment processes

Even though there are great variations in the characteristics of Scandinavian wastewater, it seems quite clear that the majority in this survey, could be characterised as having a high fraction of suspended organic matter, a considerable fraction of suspended phosphorus and a surprisingly high fraction of suspended nitrogen. It is also reason to believe that many plants have a very low fraction of organic matter on readily biodegradable form. Below we shall discuss what implications such wastewater characteristics may have on various choices that have to be made when selecting the total wastewater treatment method.

Conventional versus enhanced primary treatment

Traditionally primary treatment by sedimentation has been used to remove suspended solids in raw wastewater. The removal efficiency is primarily governed by the size of the particles constituting the suspended matter and the hydraulic surface load on the settling tank. Typically removals of around 50 % with respect to SS and around 30 % with respect to BOD at surface loading rates in the order of 2-2,5 m/h are experienced, corresponding to removal of particles down to around 100 µm. There may be different reasons for including a primary treatment step. In most cases, however, it is used to lower the organic loading on the proceeding biological step. Even at a BOD-removal of 30 %, primary treatment is very cost-effective. If BOD-removal is considered the important factor for using primary treatment, one would gain a lot by enhancing the primary treatment step efficiency.

Enhancing particle separation by coagulation

The traditional way of enhancing separation of colloidal matter and fine particles, is by coagulation/flocculation. Table 5 demonstrates what can be achieved by primary precipitation in wastewater with characteristics like the ones described above.

The downside of traditional chemical primary precipitation is the increased sludge production as compared to primary settling only, partly as results of improved SS-removal but mainly due to precipitated material. The sludge produced during coagulation consists basically of the suspended solids removed and the coagulated/precipitated matter, as described below (Ødegaard, 1994):

$$SP = SS_{in} - SS_{out} + K_{prec} \cdot D$$

SP	= sludge production (g SS/m ³)
SS _{in} , SS _{out}	= SS concentration in influent and effluent respectively (g SS/m ³)
K _{prec}	= sludge production coefficient (g SS/g Me), around 4-5 for Fe and 6-7 for Al
D	= dosage of metal coagulant (g Me/m ³)

Table 5. Average treatment results in 23 larger (>2.000 pe) (Ødegaard, 1992) and 35 smaller (<2.000 pe) primary precipitation plants in Norway (Ødegaard and Skrivseth, 1997)

Parameter	Average inlet concentration	Average outlet concentration	Average treatment efficiency
SS (mg/l)			
Large plants	233 ± 171	17,3 ± 10,0	92,0
Small plants	226 ± 150	22,3 ± 16,6	90,1
COD (mg/l)			
Large plants	505 ± 243	108 ± 40	78,6
Small plants	494 ± 90	121 ± 72	75,5
Tot P (mg/l)			
Large plants	5,40 ± 3,01	0,28 ± 0,14	94,8
Small plants	5,33 ± 2,26	0,50 ± 0,46	90,6

One can reduce sludge production only by reducing K or D or both. Plant operators have experienced that the best phosphate removal takes place at pH around 6 and they add enough of the acid metal coagulant to get down to this pH. This results in overdosing considering the stoichiometric need and to precipitation of metal hydroxide, i.e. excessive sludge production. If particle removal is focused on, one may, however, lower the dosage without ruining coagulation efficiency by replacing part of the metal cation with an organic polymeric cation. The cation will not result in precipitation and only add very little extra sludge production caused by coagulation. This is demonstrated in figure 7 that gives the ratios between the amount of SS produced (sludge production) and the amount of SS removed ($SS_{in} - SS_{out}$) as well as removal efficiency ($(1 - SS_{out}/SS_{in})100\%$) for situations where iron only or a low dose of iron (5,5 mg Fe/l) combined with a cation polymer were used in jar-tests (Ødegaard, 1998).

In figure 7a it is shown that the sludge production caused by precipitation was increasing with metal dosage and was almost as high as that caused by the SS-removal at dosages above 20-25 mg Fe/l, where removal efficiencies over 90 % is achieved. In figure 7b, however, where metal cation is replaced by polymer cation, it is shown that close to nothing was precipitated without losing much on removal efficiencies at optimal dosages of polymer.

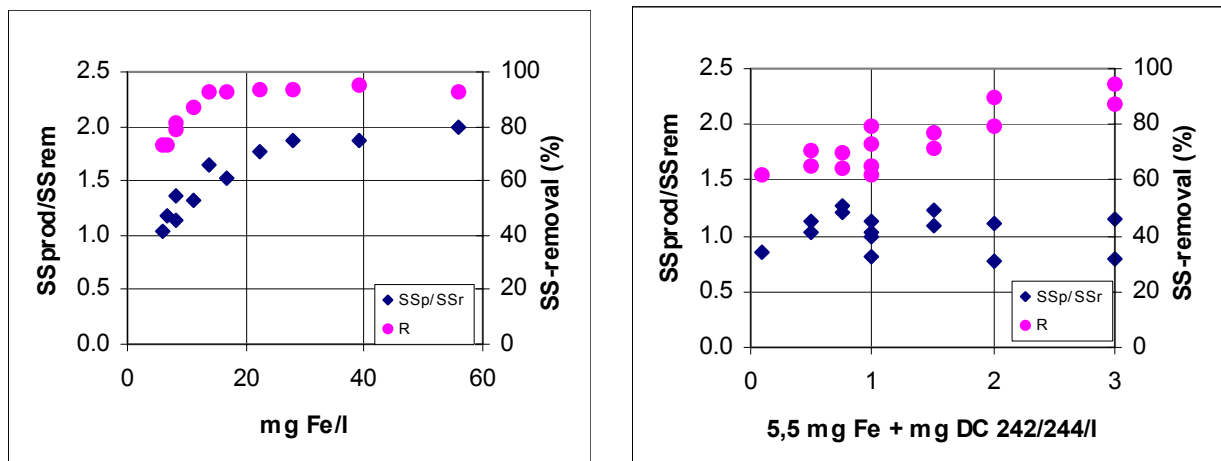


Figure 7 Comparison of primary particle separation at different dosage scenarios

When considering the fact that the soluble fraction of phosphate seem to constitute only about 50 % (or less) of the total phosphate, there are reasons to believe that most plants using primary precipitation are overdosing, thus creating excessive sludge production. Combining a low metal cation dose with a cationic polymer dose may lead to acceptable SS, COD and P-removal at minimised sludge production.

Enhancing particle separation by coarse filtration

Another approach that may be used, is too choose a physical treatment method that is able to remove smaller particles than can be expected by primary settling. Sand filtration would obviously yield better SS-removal than primary sedimentation but cannot be used because of the low sludge carrying capacity (low porosity). With a coarser filter with a high porosity, such problems might be overcome. This has lead to the development of coarse, floating filters (Ødegaard et al, 1998). Results from experiments carried out with the so called Kaldnes floating filter, that uses the Kaldnes biofilm carriers as filter medium, are reported elsewhere (Ødegaard et al, 1998)(Ødegaard and Helness, 1998). Here only a table showing typical performances from a pilot plant operated on presieved (1,5 mm or 0,3 mm sieve opening) raw wastewater under various cationic polymer dosing conditions shall be included (see table 5).

Table 5 Results and operating conditions for primary treatment in a coarse floating filter with KMT biofilm carriers as filter bed

N Runs	Pre- treatm. Mm	Polym dose mg/l	Filter rate m/h	Run time hrs	SS in mg/l	SS out mg/l	SS %	COD in mg/l	COD out mg/l	COD %
2	1,5	none	7,5	17,3	137	33,3	75,7	344	109	68,3
1	0,3	none	7,5	54,6	168	45,0	73,2	348	134	61,5
1	0,3	3,0	7,5	97,1	152	28,1	81,4	290	72,1	75,1
1	0,3	5,0	7,5	25,1	147	27,2	81,5	249	63,1	74,7
3	1,5	3,3	7,5	14,7	181	38,3	78,9	340	93,5	72,5
3	1,5	5,5	7,5	5,3	172	16,2	90,6	283	54,9	80,6

It was found that the SS-removal efficiency could be higher than 75 % at filtration rates at 7,5 m/h or lower without the use of coagulating chemicals and that SS-removal efficiencies over 80 % could be obtained when cationic polymers, that did not contribute to sludge production by precipitation were used. The main mechanisms that are expected to contribute to the removal of suspended matter in such a floating filter, are flocculation/sedimentation and adhesion to biofilms within the filter.

Chemical versus biological secondary treatment

In order to be able to nitrify, the organic matter concentration has to be reduced to such low levels that the autotrophs are not out-competed by the heterotrophs in their struggle for oxygen. With wastewater characteristics like the one dominating in Scandinavia, it is not evident that biological treatment is more favourable than chemical coagulation for pre-treatment before nitrification.

This can be visualised through an analysis of treatment efficiencies and effluent concentrations that can be calculated based on assumptions regarding removal of each of the fractions (see figure 8). Let us assume that chemical treatment can give 90 % removal of the suspended COD-fraction and 40 % of soluble and colloidal COD. This is a reasonable assumption since the colloidal fraction of COD typically is 15 % of total COD. Let us further assume that the biological plant can remove 85 % of COD_{SS} and 80 % of $COD_{filtered}$, which is reasonable since about 15-20 % of the COD_{total} is inert.

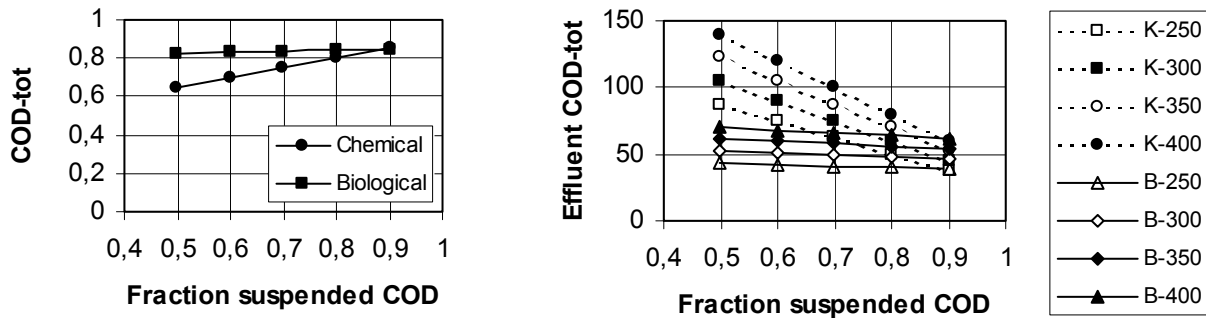


Figure 8 Comparison between calculated treatment efficiencies and effluent concentrations for various fractions of suspended COD

It is demonstrated that when the suspended fraction comes above 70 %, there is really very little difference between chemical and biological treatment when COD-removal is considered. It is also obvious that chemical treatment is very dependent upon the suspended fraction, biological treatment is far less dependent. Chemical coagulation may be considerably cheaper, though, especially when a primary step is available.

Biofilm processes versus activated sludge processes

The fact that a large fraction of the organic matter is in particulate, form does not necessarily mean that it is not available as carbon source. It means, however, that there must be an opportunity for hydrolysis of the particulate organic matter. Not enough is known about the hydrolysis of organic particles in wastewater. It is, however, reason to believe that the hydrolysis process is a "time dependent process". This means that the time available for hydrolysis plays a role for the degree of hydrolysis. It is quite probable that the organic matter adsorbed to the biomass itself plays an important role as carbon source. Consequently the amount of carbon source that can be extracted from the biomass of a reactor will be dependent upon the amount of biomass in that reactor. This means that activated sludge processes probably can utilise more of the particulate carbon source than biofilm processes, simply because the total biomass is larger and the residence time longer as a consequence of the larger reactor volume in activated sludge processes.

Activated sludge processes are to a much greater extent than biofilm processes based on flocculation. Consider an activated sludge tank as a flocculation reactor. The water in the reactor is mixed, it has a significant residence time, it contains a high floc volume and the flow pattern is often leaning towards plug flow. All these factors influence on the degree of flocculation that will occur. When looking at the activated sludge reactor in this way, it is obvious that particulate organic matter can be enmeshed into the biomass flocs and hydrolysed. The particulate, slowly biodegradable organic matter can be extensively utilised because it is associated with a biomass that has a long residence time in the system, namely the sludge age.

If we, on the other hand, consider a biofilm reactor (at least many of them), one may think of the particulate matter as particles "on their way through". In some biofilm reactors, for instance the trickling filter, the time in which the water (carrying particles) is in touch with the biomass is very short - a few minutes. In a moving bed reactor is a bit longer (about 1 hr) and in some fixed bed filters (like Biofor) it may be some hours. Nevertheless, it is short as compared to activated sludge. This is, of course, a simplistic picture. Also in biofilms, we have enmeshment in the biomass structure, but it is reason to believe that this is less significant than in activated sludge. In figure 9 a conceptual model of what is taking place with respect to conversion of COD in a biofilm reactor based on the Kaldnes moving bed process is illustrated, as an example.

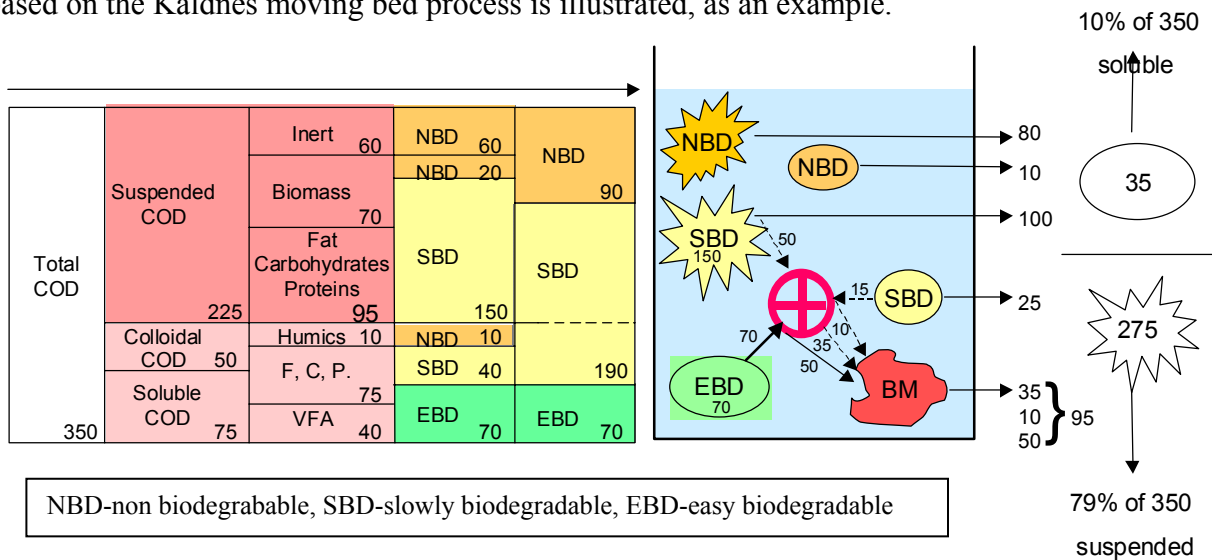


Figure 9 A conceptual model of the conversion of COD in a moving bed biofilm reactor

Most of the particulate organic matter, 180 mg/l (80 mg/l of non-biodegradable and 100 mg/l of slowly biodegradable) passes unchanged through the reactor and can be separated together with the produced biomass downstream. A certain fraction (50 mg/l) is, however, caught in the attached biomass and hydrolysed there. Part of the soluble, slowly biodegradable (15 mg/l) is also hydrolysed by the attached biomass and converted to new cell material as is also the easily biodegradable, soluble matter (79 mg/l). The production of new biomass is calculated to be 95 mg/l. The example gives as result that 10 % (35 mg COD/l) of the total COD leaves the reactor as soluble matter out of which 10 mg/l is non biodegradable (inert) and 25 mg/l is slowly biodegradable. About 275 mg/l leaves the reactor as particulate COD out of which 95 mg/l is biomass that have been produced during the process, 100 mg/l is slowly biodegradable particulate matter that never was hydrolysed and 80 mg/l is non-biodegradable particulate organic matter.

There is disagreement among researchers about where in the reactor hydrolysis actually occur, in the bulk liquid or, as assumed above, in the attached biomass. It seems, however, (Confer et al, 1998)(Janning, 1998) that the dominant portion of the hydrolytic activity is cell-associated. In biological filters (BIOFOR, BIOSTYR etc) the organic particles are caught and retained within the filter and the possibility for hydrolysis may be greater here. Janning (1998) indicated that 10-15 % of particulate organic matter retained in the filter was completely oxidised to inorganic carbon within 24 hrs. The utilisation of the particulate material as carbon source in these filters is, of course, dependent upon the filter run time, since the major part of the organic matter will be washed out during filter washing.

Generally speaking, these examples indicate that biofilm processes are more advantageous when the water has a low content of particulate organic matter. Biofilm processes are suitable in raw waters that have a high fraction of organic matter on particulate form when this is removed ahead of the bioreactor (i.e. pre-coagulation) leaving a dilute water with a low content of easily biodegradable matter for the biofilm process. Activated sludge processes are more advantageous when the water has a higher fraction of particulate organic matter since this process is better in hydrolysing this particulate COD.

Pre-denitrification versus post-denitrification

Obviously, pre-denitrification processes are more dependent upon the wastewater characteristics than post-denitrification processes, because of the need for carbon source being present in the raw water. In the wastewaters that has the typical characteristics shown in the survey, it may be needed that measures are taken in order to improve the situation with respect to the carbon source availability. Possible measures are :

- Provide conditions favourable for main-stream hydrolysis
- Establish side-stream biological hydrolysis
- Regain carbon source from thermal sludge hydrolysis in the sludge line

In biological nitrogen removal processes, the biological sludge is "starved" and containing far less organic matter that may be hydrolysed than primary sludge. Therefore hydrolysis will most effectively be carried out on primary sludge produced with or without the addition of coagulants. It has been shown (Æsøy, 1994) that the production rate of soluble organic matter (COD_s) was directly proportional to the sludge volatile solids concentration. The average yield was found to be 11,1 % while 66,2 % of the total soluble organic matter was present as volatile fatty acids

The choice between pre- and post-denitrification is, however, also coupled to the choice between activated sludge and biofilm processes. Generally speaking, the cost of bioreactor volume (NOK/m^3) is much higher in biofilm reactors and consequently one will have much more to gain by reducing the load ahead of a biofilm reactor (for instance by enhanced pre-treatment - mechanically, chemically or biologically) than ahead of an activated sludge reactor.

The nitrification rate in biofilm systems depends more heavily on the bulk oxygen concentration than in activated sludge systems and often much higher O_2 -concentration are maintained in the bioreactor of nitrifying biofilm systems than in activated sludge systems. When there is a need for a high nitrogen removal, a high recirculation ratio is needed. Biofilm systems based on pre-denitrification alone will consume much of the available carbon source on oxygen as the electron acceptor. Activated sludge processes, on the other hand have longer retention times and can utilise particulate organic matter better as carbon source. In this case pre-denitrification is more suited and the extent of pre-treatment ought not be too extensive.

Generally therefore, we may conclude that process trains based on enhanced pre-treatment (mechanical, chemical or biological), biofilm reactors and post-denitrification may be more suitable for wastewater with a high fraction of particulate COD, a low BSCOD/N-ratio, and a strict effluent standard on nitrogen removal. On the other hand process trains based on activated sludge with no primary treatment and pre-denitrification is best suited for wastewater with a fraction of suspended COD and a high fraction of easily biodegradable COD.

Chemical versus biological P-removal

Even though most of the phosphorous in wastewater is present on soluble form, primarily as ortho-phosphate, the survey shows that a surprisingly high fraction of phosphorous appears on particulate form. Chemical treatment removes both soluble and not soluble phosphorous, but so does also biological phosphate removal.

In chemical treatment soluble phosphate may be removed by precipitation/flocculation/separation, while non-soluble phosphate may be removed by coagulation/flocculation/separation. Fortunately the optimal process conditions for precipitation (by alum and iron) are very similar to those for coagulation. In biological treatment phosphate may be removed by at least four different mechanisms :

1. Enhanced phosphate uptake (bio-P)
2. Phosphate assimilation (cell-P)
3. Phosphate precipitation (metal-P)
4. Flocculation of phosphate containing particles (colloidal and suspended) (floc.-P)

In bio-P removal research, most of the emphasis has been directed towards the first of these mechanism. This may be understandable since this mechanism is the most "exotic" one from a researchers point of view. Enhanced biological phosphate uptake is, however, totally dependent upon the presence of readily biodegradable organic matter, i.e. volatile fatty acids. The survey gives reason to believe that the VFA concentration in many of the Scandinavian wastewaters is low. Nevertheless it has been demonstrated in practice that acceptable P-removal has been achieved in many biological treatment plants, even though the availability of VFA has been less than desired. Therefore, the other removal mechanisms may play a more important role than we think. Aspegren (1995) demonstrated that mechanism 2 and 3 were quite important.

In wastewater with characteristics common in Scandinavia, it is, however, reason to believe that also the flocculation mechanism plays a very important role in removing the particulate P. Assimilation plays an important role in removing the soluble P. Figures 10 is made to illustrate this. In this figure it is assumed that 80 % of the suspended P is removed by flocculation/separation while 50 % of the soluble COD and 20 % of the suspended COD leads to the production of biomass (yield: 0,4 g SS/g COD) that contains 1,5 % P.

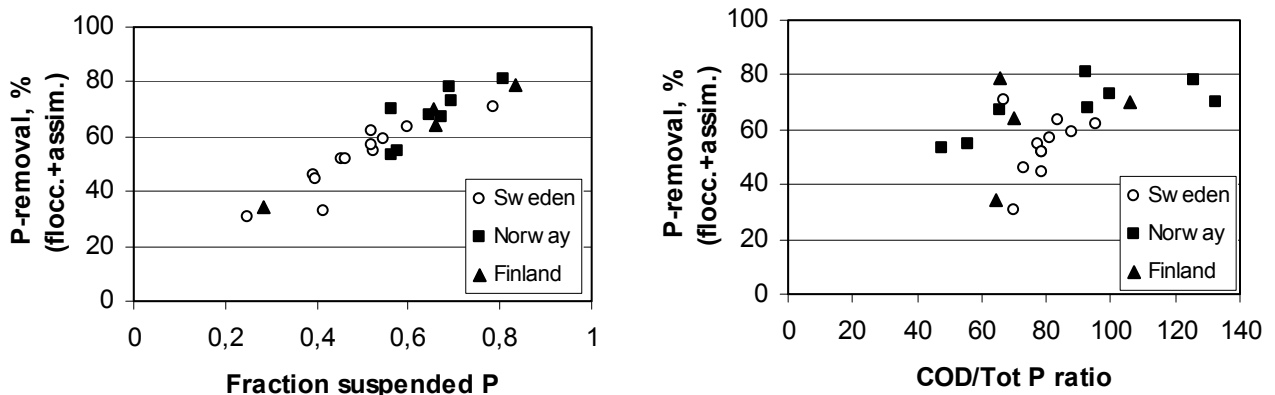


Figure 10. Calculated removal of P caused by bioflocculation and assimilation versus
a) fraction suspended P and b) COD/tot P-ratio in Scandinavian plants

It can be seen that the removal that can be caused by the sum of the bio-flocculation and assimilation mechanisms, increases with increasing fraction of suspended P and increasing COD/P-ratio. It is interesting to note, that if one can accept these assumptions, more than 50 % of the phosphorous removal can be explained by the sum of the bio-flocculation and assimilation mechanisms in most cases. In many cases more than 70 % may be caused by these mechanisms. It is also interesting to note that in wastewater with a high fraction of suspended P, like in Norway, biological treatment may give high P-removal efficiencies even if the water has undesirable characteristics for enhanced phosphate uptake. Several of the Finnish plants are in the same situation, but in these plants assimilation of phosphate plays a more important role than in the Norwegian plants where bio-flocculation would be the dominant mechanism.

One should not forget that these are only calculations and not observations. They should, however, contribute to realising that biological phosphate removal is based on many different mechanisms that are not always well understood.

Conclusions

It has been demonstrated that the wastewater in many of the treatment plants in the Nordic countries (Finland, Sweden and Norway) can be characterised as having:

- a high fraction of organic matter on suspended form
- a considerable fraction of phosphorous on suspended form
- a surprisingly high fraction of the nitrogen on suspended form

The wastewater in Norway was found to most dilute and the one in Finland most concentrated. In many plants the fraction of organic matter on readily biodegradable form can be expected to be quite low and the available carbon source for pre-denitrification and biological P-removal must be expected to be insufficient in many cases, especially in the Norwegian wastewater.

With these wastewater characteristics, much can economically be gained by enhancing particle separation in primary treatment, either by coagulation or by coarse filtration. By replacing some of the metal cation by a polymeric cation, excess sludge production can be minimised without destroying the phosphate removal efficiency, since the soluble phosphate concentration is very low in many cases.

For plants with strict N- and P-standards and a wastewater characterised by having a large fraction of the organic matter on particulate form, and a low fraction of readily biodegradable organic matter, there are two extreme process solutions, that may encompass many theme variations :

1. A compact treatment train based on enhanced particle separation by coagulation in the primary step followed by a combined pre- and post-denitrification biofilm process. Carbon source must be added or provided for by side-stream sludge hydrolysis (biological or thermal)
2. A voluminous treatment train based on a minimum of pre-treatment, followed by pre-denitrification (possibly combined with enhanced bio-P removal) in activated sludge with simultaneous precipitation. Side-stream biological sludge hydrolysis may be required in order to avoid addition of external carbon source.

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