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In-out ultrafiltration in tertiary wastewater applications — Comparison of different operational strategies

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ABSTRACT

Regional water scarce, climate change and environmental requirements are making waste water re-use a feasible alternative on the industrial and municipal water supply sector. Nowadays, ultrafiltration plays a major role in the treatment of municipal and industrial tertiary waste water. It is an ideal stand-alone technology to treat waste water and produce a constant quality treated water which is used mainly for irrigation, aquifer replenishment or as a pretreatment to a reverse osmosis step. Due to the UF particles, bacteria and even viruses are rejected. Depending on the quality of the secondary effluent in regard of potential membrane foulants (e.g. dissolved or colloidal organic substances), operating parameters and required chemicals for the pretreatment (e.g. coagulants) and different cleaning processes can have a significant impact on the design and also on the capital and on the operational costs. This paper presents investigations and optimization of different operating strategies to ensure a proper UF system design while ensuring reliable operational parameters and trustworthy costs. Results shown in the paper originate from several pilot tests and full-scale experiences in different countries. The standard inge® UF membrane process for tertiary effluent treatment using continuous inline coagulation and automatic chemical enhanced backwashes (CEB) is compared to three UF pretreatments variants associated to their own operating process: 1) UF pretreatment with (biological active) sand / gravel filtration, 2) advanced coagulation process (intermittent inline coagulation upstream UF) and 3) finally operation without addition of coagulant. The obtained information and experiences are compared and evaluated in regard of the overall UF design and cost impacts as well as UF filtrate quality. The paper proves that the operational costs can be significantly reduced when applying an intermittent inline coagulation as coating process.

Keywords: Inline coagulation; Reuse; Ultrafiltration; Wastewater

1. Introduction

Drinking water is the most important food item for all living beings. However, conditions in various regions and countries can vary widely. Concerning the continuing climate change, the frequency and magnitude of extreme weather are increasing. There are longer droughts combined with dispersion of deserts and periods of intense rain events combined with flooding. There are either water scarcity or polluted water sources. However, it is not only vital to have access to water in general, but also to have access to clean water.

It's well known that UF provides superior water quality compared to conventional treatment technology and delivers a continuously good filtrate quality independent from feed water quality variability caused by, for instance, seasonal changes. This means that also highly polluted water can be securely purified and pathogenic ingredients will be rejected in order to be able to use the water as pure drinking water.

Therefore, treating effluent from municipal waste water has been considered as a valid option to get clean water mainly for reuse or irrigation purposes [1]. Several different treatment procedures including the operation of UF membranes were

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studied [2]. It has been demonstrated that the health risks of reusing water in agriculture are minimal as long as its biological quality meets established criteria [3,4]. Depending on the quality of the secondary effluent in regard of potential membrane foulants (e.g. dissolved or colloidal organic substances), operating parameters and required chemicals for the pretreatment (e.g. coagulants) and different cleaning processes can have a significant impact on the design and also on the capital and on the operational costs. The aim is to achieve a stable operation of the plant at low transmembrane pressures, to get high elimination rates of important water ingredients and to acquire low operational costs.

As coagulant is one of the most expensive components of the operation, alternative operations with sufficient results need to be explored. Therefore, several tests with e.g. intermittent coagulant dosing or without the addition of any flocculant but with chlorinated backwashes were executed and evaluated. As the omission of coagulant, also in parts, influences the operation of the UF module, this paper presents the results of the different operations. The analytical elimination rates and also the calculated operational costs of the runs with the adjusted parameters are discussed.

2. Material and methods

2.1. Membrane and modules

Back in 2000, inge® launched the Multibore® membrane which is a fiber (Fig. 1) consisting of a foamy homogenous support structure containing seven capillaries, or channels.

The inner layer of the seven capillaries represents the very thin active filtration surface. The foamy support structure in between the capillaries shows a permeability that is around 1000 times higher than that of the filtration surface so that an equal distribution throughout the whole cross-section of the fiber can be guaranteed. The Multibore® fibers are made from modified polyethersulphone (PES) with a high pH tolerance from 1–13 which allows efficient cleanings even in extreme conditions. The inner diameter of each individual capillary is 0.9 or 1.5 mm. The nominal pore size of the filtration layer is approximately 20 nm. This unique structure enables a very high stability to the membrane.

2.2. Pilot Plant

Pilot plants are fully automated units and basically consist of a feed pump, a backwash pump and a filtrate tank, chemical dosage pumps for three different chemicals, and different measurement devices (pH-value, turbidity, flow rate, pressure and temperature). All pumps are controlled by frequency converters to ensure a stable flow rate. Additionally, a dosage pump for coagulant is installed in the feed water pipe.

Fullscale pilot plants are typically equipped with dizzer® XL modules developing a filtration area between 25 and 70 m² depending of the length of the module (1.2–1.7 m) and the capillary diameters (0.9 or 1.5 mm).

Results presented in this paper were generated with full-scale pilot units equipped with such modules and with a labpilot with 0.22 m² module (length of 1.5 m, 0.9 mm capillary diameter).

2.3. Operating process

Filtration with Multibore® membranes takes place in the so called "in-out-mode". This procedure assures an ongoing and equal overflow on the feed side on which a cake layer is formed. The backwash (BW) is carried out on a regular basis (from 20 to 120 min) for relatively short time periods (30–60 s) with only a small amount of filtrate. The backwash is composed of two steps during which treated water (permeate) is send under pressure inside the fibers. During the first step, backwash waste water exits from the bottom end of the module while during the second step, the backwash waste water is wasted via the upper end of the module. Thanks to this protocol, the cake layer is loosened and removed out of the module at every backwash. Operation modes are shown in Fig. 2.

2.4. Analytical data

The analytical parameters which were determined for the presented tests are the following:

- Organic parameters: parameter for fouling potential
  - Filtered chemical oxygen demand ($COD_{filtered}$)
  - Biological oxygen demand at 5 days (BOD_5)

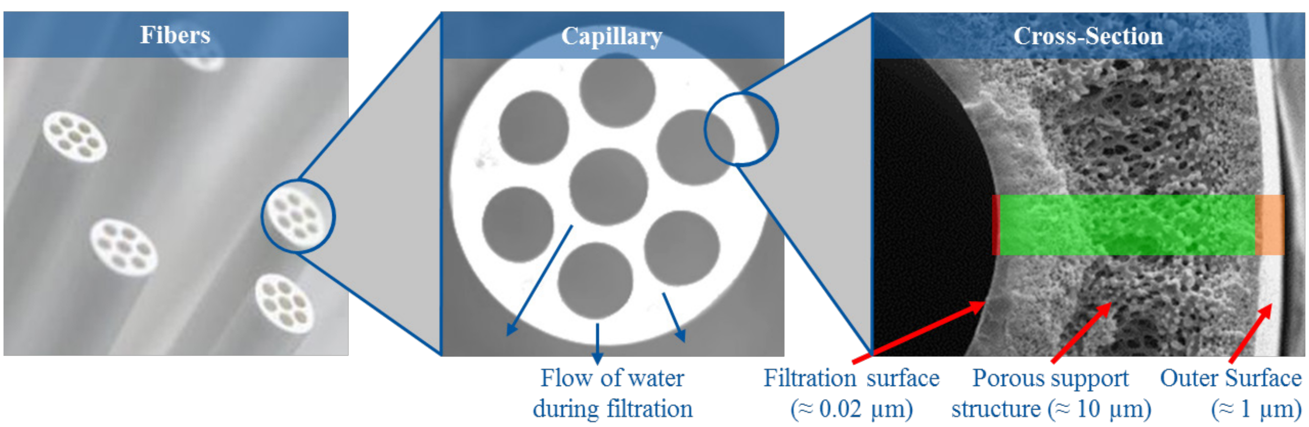

Fig. 1. Multibore® membrane.

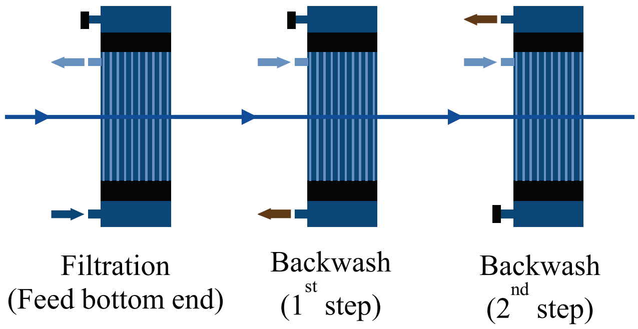

Fig. 2. Direction of flow in a dizzer® module during filtration and backwash mode.

   - Dissolved organic carbon (DOC)
   - Spectral absorption coefficient at 254 nm (SAC_{254nm})
- Inorganic parameters: parameter for biological activity
   - Total phosphorus ($P\text{-}PO_{4,\ total}$)
   - Total ammonia ($N\text{-}NH_4$)

The measurement of the silt density index at 15 min (SDI_{15}) was not always possible due to the size of the pilot plants. These values will be determined in other waste water applications.

3. Results and discussion

The experiments were carried out at the municipal sewage plant in the town Eching, Germany, which treats a mix of municipal and industrial waste water, corresponding to of about 90,000 inhabitant-equivalent. The plant consists of multiple stages as schematically shown in Fig. 3. The first stage is a primary clarification preceded by fine screens and sand catcher where coarse components like fat or sand are eliminated. The second stage is a biological treatment consisting of denitrification and aeration basin. In the denitrification basin, microorganisms convert nitrate to molecular nitrogen. In the aeration basin, the nitrification of ammonium to nitrate takes place. The next step of the waste water treatment plant is the phosphate elimination according to the addition of an aluminum (Al) based flocculant with contingents of iron. In the final clarifier the separation of the solid and liquid happens. Some relevant analytical measurements of the treatment plant effluent are listed in Table 1.

Different tests were performed on the secondary effluent exiting the plant. First tests were conducted on the secondary effluent with inline coagulant dosing before the UF module. Coagulant dosing took place either continuously (i.e. during the whole filtration cycle) or intermittently (so called coating procedure) which corresponds to a dosing during the first minutes of the filtration cycle. During the second set of trials, coagulant addition was not implemented but chlorinated backwashes were performed at two different chlorine (Cl_2) concentrations. For the third set of tests, a sand filter (SF) was installed upstream the UF and coagulant addition was performed either upstream the SF or upstream the UF. During the first and third set of trials, polyaluminumchloride (PACl) was selected as coagulant to achieve phosphorus removal. Table 2 summarizes the different tests conducted to evaluate the difference in operation depending on the adjusted parameters.

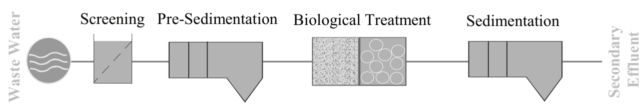

Fig. 3. Plant treatment schematic.

Table 1
Average analytical data

Parameter	Average values	
$COD_{filtered}$	30.0	mg/L
BOD_5	6.5	mg/L
DOC	5.0	mg/L
SAC_{254nm}	14.0	/m
$PO_{4,\ total}$	0.6	mg/L

Table 2
Overview of the different tests

I	Inline coagulant dosing	Continuous coagulant dosing
		Intermittent coagulant dosing (coating)
II	Chlorinated backwash	No coagulant dosing
III	With sand filtration	Coagulant dosing upstream sand filtration
		Coagulant dosing upstream ultrafiltration

By remote control and continuous data recording, the important operational parameters such as permeability and TMP were evaluated, both of them being criteria for a stable operation.

3.1. Operation with continuous / intermittent coagulant dosing

This test series was conducted with inline coagulant dosing upstream the UF either continuously or intermittently. Fig. 4 shows the flow diagram of these runs. Tests were carried out under identical operational parameters (Table 3).

3.1.1. Continuous coagulant dosing – 5 mg/L Al

This first series of tests was conducted with continuous coagulant dosing at a concentration of 5 mg/L Al, optimal value defined during previous tests on wastewater at other locations.

As shown in Fig. 5, stable operation is achieved with average permeability of 170 ± 95 L/(m²·h·bar) at 20°C and average TMP of 450 ± 190 mbar (TMP rises by of about 300 mbar during one filtration cycle). As the TMP after backwash always goes back more or less to the previous value, one can conclude that the aluminum fouling layer which built up during one filtration cycle is almost completely removed from the membrane surface area thanks to a normal backwash.

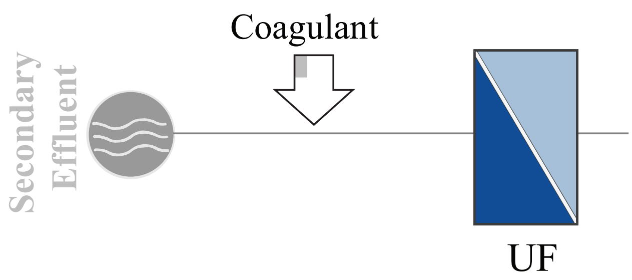

Fig. 4. Flow diagram – operation continuous / intermittent coagulant dosing.

Table 3
Operational parameters – 5 mg/L Al

Parameter	Value	
Flux	70	L/(m²·h)
Filtration time	40	min
Backwash duration (1st/ 2nd step)	30/30	sec
CEB (caustic + acid)	2	x/day
Recovery	~ 91	%

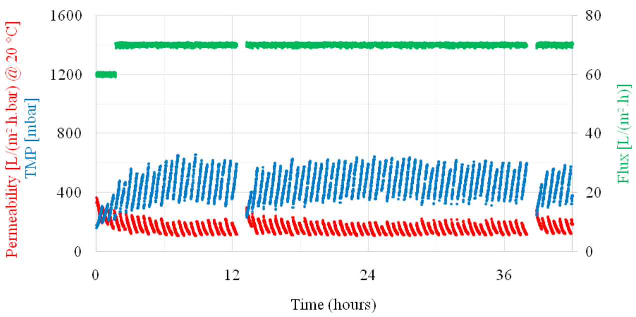

Fig. 5. Operation with continuous coagulant dosing – 5 mg/L Al.

Preliminary tests showed that the chemical enhanced backwash (CEB) frequency originally set at twice a day can be extended to once a day. Under this condition, the TMP just after a CEB is of about 240–250 mbar showing the beneficial effect of a CEB in further removing the fouling layer.

With a continuous addition of 5 mg/L Al, the removal of COD $_{filtered}$ and $PO_{4,total}$ is respectively ~ 43% and ~ 44% (Table 4).

3.1.2. Intermittent coagulant dosing – 5 mg/L Al

For the second series of tests, the coagulant was dosed intermittently at a concentration of 5 mg/L of Al for the first four minutes of the filtration cycle. As previously, the operation is stable but at different levels of permeability and TMP (Fig. 6). The average permeability is slightly higher (160 L/(m²·h·bar) at 20°C) but with an increased amplitude (± 70 L/(m²·h·bar) at 20°C). The average TMP is also higher as well as its amplitude (540 ± 280 mbar). One can note that the TMP cannot be fully restored after every backwash, the normal backwash not completely removing the fouling layer from the membrane. In this case, twice daily CEB's are necessary to bring the TMP back to the basis.

Compared to continuous addition, removal (Table 5) of COD $_{filtered}$ is lower (~ 24%) but $PO_{4,total}$ removal is higher (~ 63%). Even if water quality was not identical during both tests, one can assume that the possible reason for lower COD removal is due to the fact that, during this test, coagulant reacts with organics only during a short period of time. The unexpected higher elimination rate of $PO_{4,total}$ is questionable and needs further investigation. The measured value for the SDI_{15} was 0.53 %/min, significantly lower than for continuous addition.

3.2. Chlorinated backwashes

To evaluate operation without any pretreatment, this series of tests (Fig. 7) was conducted without coagulant addition but with performance of chlorinated backwashes.

For the Multibore® membrane, the typical Cl_2 dosing amount during a CEB or disinfection is 500 mg/L at a pH value > 9.5. In some cases, up to 1000 mg/L Cl_2 is used. To optimize the overall Cl_2 consumption and the impact of Cl_2 during a backwash, different Cl_2 concentrations were tested, 150 and 50 mg/L Cl_2, at pH adjusted to 9.5. Running parameters are listed in Table 6.

3.2.1. Backwashes with ~ 150 mg/L Cl_2

The tests were started with addition of around 150 mg/L Cl_2 during the backwash. As a high fouling potential was

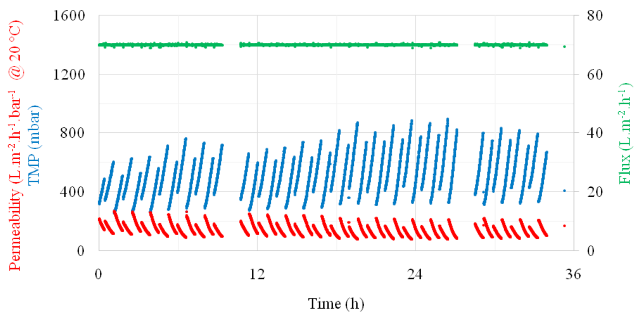

Fig. 6. Operation with intermittent coagulant dosing – 5 mg/L Al.

Table 4
Analytical data – Continuous dosing – 5 mg/L Al

Parameter	Sec. eff.*	UF filtrate**
COD $_{filtered}$, mg/l	30.60	17.55
$PO_{4,total}$, mg/l	0.54	0.30
SDI_{15}, %/min	–	1.32

Table 5
Analytical data – Intermittent dosing – 5 mg/L Al

Parameter	Sec. eff.*	UF filtrate**
COD $_{filtered}$, mg/l	17.70	13.50
$PO_{4,total}$, mg/l	0.54	0.20
SDI_{15}, %/min	–	0.53

Fig. 7. Flow diagram – Chlorinated backwashes.

Table 6
Operational parameter – Chlorinated backwashes

Parameter	Chlorine addition during BW	
	150 mg/L Cl_2	50 mg/L Cl_2
Flux, L/(m²·h)	60	70
Filtration duration, min	45	30
Backwash duration (1st/ 2nd step), s	30/15	30/15
CEB (caustic + acid), x/d	1	1
Recovery, %	~ 92	~ 91

expected, this series was started with a flux rate of 60 L/(m²·h). As for all previous tests, the operation is very stable (Fig. 8) with average permeability of 190 ± 40 L/(m²·h·bar) at 20°C and average TMP of 300 ± 60 mbar (TMP increase of 120 mbar during one filtration cycle). The slight observed increase of the TMP after each backwash is the sign that the normal backwash cannot completely remove the cake layer from the membrane. As previously noted, the initial TMP can be restored thanks to daily CEB's.

According to the analytical data (Table 7), the following final elimination rates were measured: $PO_{4,total}$ ~85% and

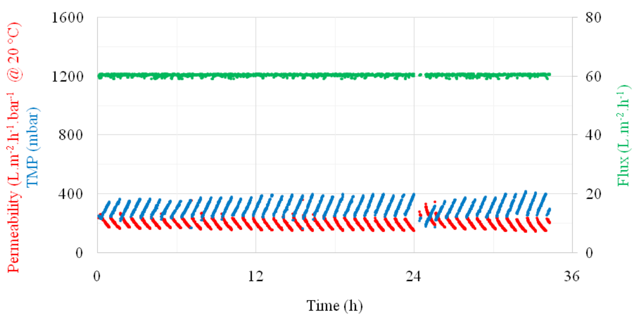

Fig. 8. Operation with chlorinated backwashes – 150 mg/L Cl_2.

Table 7
Analytical data – Chlorinated backwashes – 150 mg/L Cl_2

Parameter	Sec. eff.*	UF filtrate**
SAC_{436nm}, 1/m	1.2	0.37
$PO_{4,total}$, mg/l	0.39	0.06

*Sec. eff.: secondary effluent
**Average value (samples taken during the whole filtration cycle mixed for measurement)

SAC_{436nm} ~ 69%. As the chlorinated backwashes should not have any influence on the $PO_{4,total}$ elimination rate, thus this result is questionable and needs further verification.

3.2.2. Backwashes with ~ 50 mg/L Cl_2

To optimize the chemical consumption, the chlorine dosing during the backwash was reduced to around 50 mg/L Cl_2 while still maintaining a flux rate of 60 L/(m²·h). As this operation was stable, the flux was then increased to 70 L/(m²·h).

Even with a slightly increase of the flux by 17%, the operation remained stable (Fig. 9) with average permeability of 100 ± 30 L/(m²·h·bar) at 20°C and average TMP of 700 ± 200 mbar. As anticipated, backwashes with 50 mg/L Cl_2 have a lower removal efficiency of the fouling layer compared to backwashes with 150 mg/l Cl_2. This results in lower average permeability and higher average TMP. The TMP increases by an average of 400 mbar during one filtration cycle, which is more than 3 times the TMP increase of the previous test. The TMP after backwash tends to increase but once again restored thanks to a CEB.

Even though, the maximum TMP and the pressure increase during the filtration were higher during the 50 mg/L Cl_2 operation compared to the 150 mg/L Cl_2 operation, the tendencies of the operation evaluation parameters were both stable.

Table 8 presents analytical data of the feed water and UF permeate. The calculated elimination rates (feed compared to UF filtrate) are: $COD_{filtered}$ ~ 47%, SAC_{436nm} ~ 90%, $PO_{4,total}$ ~ 95%. Compared to the continuous and intermittent coagulant dosing, the $COD_{filtered}$ removal is similar. As $COD_{filtered}$ measurement for the test with backwashes at 150 mg/L free Cl_2 was not performed, one can only assume that removal would be similar. The $PO_{4,total}$ removal is higher during the

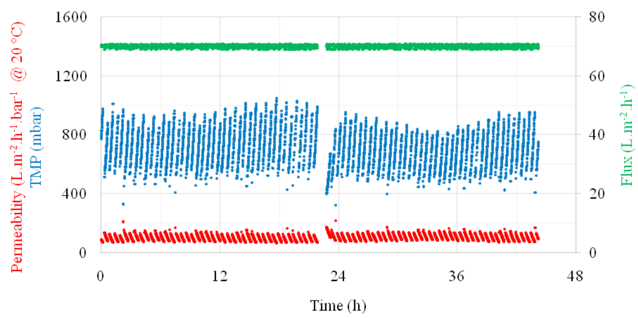

Fig. 9. Operation with chlorinated backwashes – 50 mg/L Cl_2.

Table 8
Analytical data – Chlorinated backwashes – 50 mg/L Cl_2

Parameter	Sec. eff.*	UF filtrate**
$COD_{filtered}$, mg/l	32.70	17.20
SAC_{436nm}, 1/m	1.90	0.10
$PO_{4,total}$, mg/l	0.85	0.08

*Sec. eff.: secondary effluent
**Average value (samples taken during the whole filtration cycle mixed for measurement)

chlorine backwash runs. As previously mentioned, chlorinated backwashes should not have any influence on the $PO_{4,total}$ elimination rate, thus these results are questionable and need further verification.

The most critical issue regarding the use of chlorinated backwashes is the formation of adsorbable organic halogen (AOX) compounds in the backwash waste water that might be then released into the environment. One can note that AOX are indicators for different specific danger potentials and are hard to dispose.

3.3. Operation with sand filtration as pretreatment

During this series of tests, a SF was used as a pretreatment of the secondary effluent. The SF contains quartz sand with a grain size of 1.6–2.5 mm, had an inner diameter of 288 mm and had a quartz sand layer height of approximately 1.2 m. The SF operated with a filtration velocity of about 4.6 m/h and was typically cleaned with a backwash executed once a day (except on weekends).

Coagulant addition was performed either upstream the SF or upstream the UF (Fig. 10) at two different concentrations (3 and 5 mg/L Al) and tests were carried out under similar operational parameters (Table 9).

3.3.1. Coagulant dosing upstream sand filtration

3.3.1.1. 3 mg/L Al

This test series was performed with coagulant dosing of 3 mg/L Al. Under these conditions, the operation (Fig. 11) is considered stable with permeabilities between 140 ± 60 L/(m²·h·bar) at 20°C, TMP between 720 ± 280 mbar and TMP increase of 300 mbar in one filtration cycle. In this case, one can see a constant increase of the TMP after backwash showing that a normal backwash is not able to remove the fouling layer from the membrane surface area completely.

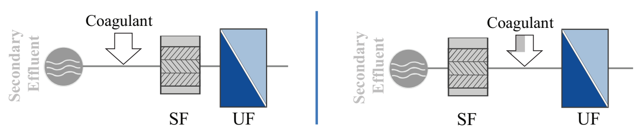

Fig. 10. Flow diagram – Operation with sand filtration.

Table 9
Operational parameter – Operation with sand filtration

Parameter	Dosing upstream SF		Dosing upstream UF	
	3 mg/L Al	5 mg/L Al	3 mg/L Al	5 mg/L Al
Flux, L/(m²·h)	70	70	70	70
Filtration time, min	45	45	45	45
Backwash duration (1st/ 2nd step), s	30/15	30/15	30/15	30/15
CEB (caustic + acid), x/d	2	2	1	2
Recovery, %	~ 93	~ 93	~ 94	~ 93

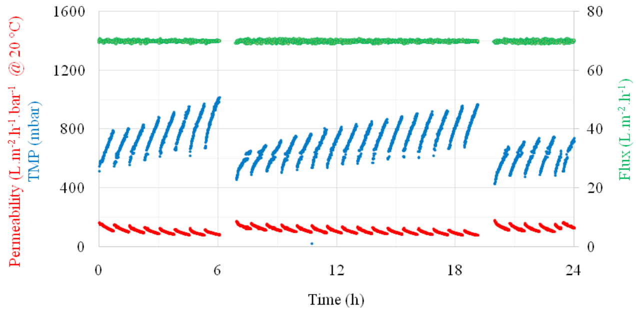

Fig. 11. Operation with coagulant dosing upstream SF – 3 mg/L Al.

One the other hand, a daily CEB is able to restore the initial TMP showing its efficiency in removing the fouling layer.

Based on water quality measurement (Table 10), the following elimination rates (SF feed compared to UF filtrate) were calculated: $COD_{filtered}$ ~ 21%, DOC ~ 26%, $PO_{4,total}$ ~ 77%, SAC_{254nm} ~ 22% and SAC_{436nm} ~ 54 %.

3.3.1.2. 5 mg/L Al

To see the influence of a higher coagulant dosing amount, the previous test was repeated with a dosing amount of 5 mg/L Al. A stable operation with permeabilities between 130 and 230 L/(m²·h·bar) at 20°C and TMP between 360 and 600 mbar was achieved (Fig. 12). During one filtration cycle the pressure increases by only ~ 80 mbar. As for the previous test, a slight increase of the TMP over the filtration cycles was observed sign that the normal backwash was not able to completely remove the fouling layer

Table 10
Analytical data – Coagulant dosing upstream SF – 3 mg/L Al

Parameter	Sec. eff.*	UF filtrate**
$COD_{filtered}$, mg/l	27.40	21.70
DOC, mg/l	6.75	5.00
SAC_{254nm}, 1/m	13.50	10.50
SAC_{436nm}, 1/m	1.20	0.55
$PO_{4,total}$, mg/l	0.35	0.08
Turbidity, NTU	8.84	< 0.1

*Sec. eff.: secondary effluent
**Average value (samples taken during the whole filtration cycle mixed for measurement)

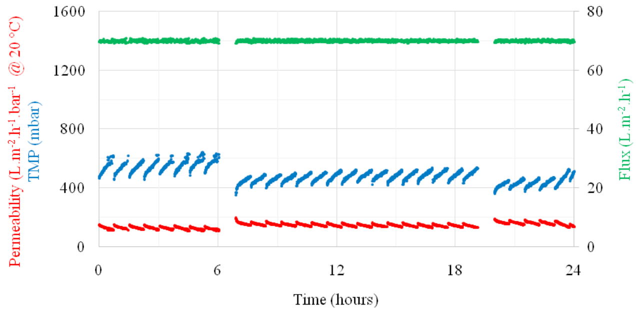

Fig. 12. Operation with coagulant dosing upstream SF – 5 mg/L Al.

from the membrane surface area. Thanks to the CEBs, the initial TMP value can be restored. One can note that with this amount of coagulant, the SF was blocked after a short time period which limit the interest of this solution.

Elimination rates shown in Table 11 (feed compared to UF filtrate) were calculated: COD $_{filtered}$ ~ 35% and SAC_{436nm} ~ 80%. Due to the increased aluminum amount being dosed before the SF, the continuous operation of the SF was not possible any more. The layer of coagulant got impermeable for the water. Thus, the SF needed to be backwashed minimum twice per day. As this procedure is not usable as standard operation, the analytical parameters were not determined and evaluated in detail.

Table 11
Analytical data – coagulant dosing upstream SF – 5 mg/L Al

Parameter	Sec. eff.*	UF filtrate**
COD $_{filtered}$, mg/l	32.20	20.90
SAC_{436nm}, 1/m	2.00	0.40
Turbidity, NTU	3.50	< 0.1

*Sec. eff.: secondary effluent
**Average value (samples taken during the whole filtration cycle mixed for measurement)

3.3.2. Coagulant dosing upstream ultrafiltration

3.3.2.1. 3 mg/L Al

To get a direct comparison between coagulant dosing before and after the SF, a test with 3 mg/L Al dosed after the SF and before the UF was conducted (operational parameters listed Table 9).

As shown in Fig. 13, the operation is very stable with average permeability of 140 ± 40 L/(m²·h·bar) at 20°C and average TMP of 700 ± 120 mbar (240 mbar TMP increase during one filtration cycle). During the first filtration cycles after the CEB the normal backwash was not able to completely remove the cake layer from the membrane. After some filtration cycles, the TMP plateaued to a certain level. The normal backwash then always could bring back the TMP to this basis. To bring the TMP back to the initial value, daily CEB is necessary.

Based on recorded analytical data (Table 12), the following final elimination rates (feed compared to UF filtrate) were calculated: COD $_{filtered}$ ~ 31%, DOC ~ 19%, $PO_{4,total}$ ~ 80%, SAC_{254nm} ~ 21% and SAC_{436nm} ~ 66%. It is remarkable that the elimination rate of the SF without prior coagulant dosing is low. Only the used coagulant supports the elimination of dissolved organic matter.

Table 12
Analytical data – Coagulant dosing upstream UF – 3 mg/L Al

Parameter	Sec. eff.*	UF filtrate**
COD $_{filtered}$, mg/l	25.70	17.80
DOC, mg/l	6.75	5.50
SAC_{254nm}, 1/m	14	11
SAC_{436nm}, 1/m	1.45	0.50
$PO_{4,total}$, mg/l	0.39	0.08
Turbidity, NTU	4.97	< 0.1

*Sec. eff.: secondary effluent
**Average value (samples taken during the whole filtration cycle mixed for measurement)

3.3.2.2. 5 mg/L Al

To see the effect of a higher coagulant dosing amount, a test with an inline injection of 5 mg/L Al prior the UF was realized (operational parameters listed in Table 9).

As shown in Fig. 14, the operation is once again considered as stable (permeabilities between 75 and 210 L/(m²·h·bar) at 20°C – TMP between 370 and 1300 mbar). Interesting to point out is that during the first filtration cycles direct after a CEB, the normal backwash is not able to completely remove the cake layer on the membrane shown by the rather quick TMP increase. After some cycles, this phenomena stops and the TMP increases less. One can also see that the TMP increase during one filtration cycle has the tendency to increase cycle after cycle which confirms the limited efficiency of the normal backwash on this type of fouling. To bring the TMP back to the initial value, only daily CEB can do it.

Water quality of the secondary effluent (SF feed) and UF permeate are listed in Table 13). Calculated elimination rates (feed compared to UF filtrate) are: COD $_{filtered}$ ~ 33%, DOC ~ 38%, $PO_{4,total}$ ~ 91%, SAC_{254nm} ~ 33% and SAC_{436nm} ~ 45%.

3.3.3. Comparison of results – dosing upstream sand filtration and upstream ultrafiltration

During all tests the pilot plant was operated with the following parameters (Table 9): flux rate 70 L/(m²·h), fil-

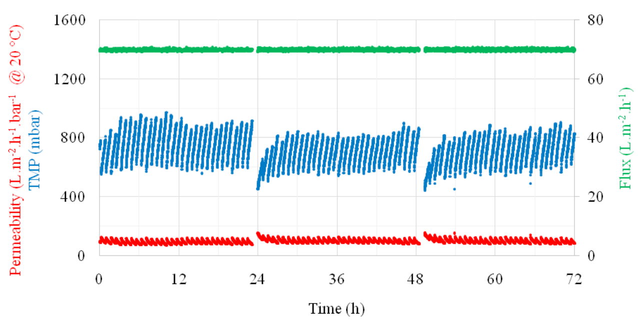

Fig. 13. Operation with coagulant dosing upstream UF – 3 mg/L Al.

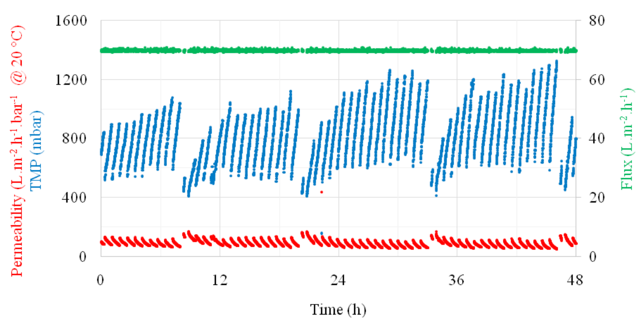

Fig. 14. Operation with coagulant dosing upstream UF – 5 mg/L Al.

Table 13
Analytical data – Coagulant dosing upstream UF – 5 mg/L Al

Parameter	Sec. eff.*	UF filtrate**
$COD_{filtered}$, mg/l	23.95	16.01
DOC, mg/l	7.90	4.90
SAC_{254nm}, 1/m	12.00	8.10
SAC_{436nm}, 1/m	1.45	0.80
$PO_{4,total}$, mg/l	0.35	0.03
Turbidity, NTU	7.25	< 0.1

*Sec. eff.: secondary effluent
**Average value (samples taken during the whole filtration cycle mixed for measurement)

tration time 45 min and backwash duration 45 s. Only the CEB frequencies and consequently the recovery rates were different.

Table 14 compares the turbidity of the water entering the SF (Feed SF) to the turbidity leaving the SF which is the one entering the UF (Feed UF). When coagulant is added upstream the SF, one can see that the turbidity is below 0.7 NTU, while the turbidity is higher without coagulant addition upstream the SF. This confirms, if needed, the well-known beneficial effect of coagulation on SF in improving the water quality.

Elimination rates by the SF only (SF) and by the combination of treatment SF and UF (SF + UF) were calculated by comparing the value of each parameter measured in the secondary effluent to the value measured in the filtrate of both the SF and the UF. Table 15 shows that in general the UF feed water quality during coagulant dosing before sand filtration is better compared to the operation with coagulant dosing before UF. For the tests with coagulant dosing before UF, the SF only removed particles, but no fouling causing ingredients. In contrast, adding PACl prior SF eliminated dissolved matter such as SAC_{436nm} and humic substances, which could pander to fouling on the membrane surface and thus to higher pressures.

For the operation SF followed by addition of coagulant and UF, two options would be possible for further optimization: continuous or intermittent coagulant dosing prior UF as presented in Chapter 3.1, because the UF feed water quality was nearly the same.

The SF without prior coagulant addition had no huge impact on the UF feed water quality. If a SF including coagulant dosing is available in an already existing plant, an additional PACl dosing prior UF would not be necessary. If the SF is available and it is arbitrary where to add the coagulant and which amount is needed, the recommendation based on the results of this paper is to use 3 mg/L Al dosing prior the UF.

For this test series, Liquid Chromatography – Organic Carbon Detection (LCOCD) analyses were implemented (Table 16). Basically, one can conclude that humic substances are eliminated through the addition of coagulant. The BIO-Polymers were only eliminated by UF. BIO-Poly-

Table 16
LCOCD Analysis

Dosage	Parameter	Feed	SF Filtrate	UF Filtrate
3 mg/L prior SF	DOC, µg/L	6.69	5.89	5.26
	BIO-polymers, µg/L	859	729	316
	Humic substances, µg/L	2090	1740	1639
	Building blocks, µg/L	1014	973	947
3 mg/L prior UF	DOC, µg/L	6.6	6.5	5.6
	BIO-polymers, µg/L	747	789	167
	Humic substances, µg/L	1931	1957	1690
	Building blocks, µg/L	953	957	915

Table 14
Turbidity – Coagulant dosing upstream SF and UF

Parameter	Coagulant dosing upstream SF				Coagulant dosing upstream UF			
	3 mg/L Al		5 mg/L Al		3 mg/L Al		5 mg/L Al	
	Feed SF	Feed UF	Feed SF	Feed UF	Feed SF	Feed UF	Feed SF	Feed UF
Turbidity, NTU	8.84	0.55	3.50	0.68	4.97	2.43	7.25	1.05

Table 15
Elimination rate – Coagulant dosing upstream SF and UF

Parameter	Coagulant dosing upstream SF				Coagulant dosing upstream UF			
	3 mg/L Al		5 mg/L Al		3 mg/L Al		5 mg/L Al	
	SF	SF + UF	SF	SF + UF	SF	SF + UF	SF	SF + UF
$COD_{filtered}$, %	~ 20	~ 21	~ 11	~ 35	~ 4	~ 31	~ 7	~ 36
DOC, %	~ 19	~ 26	–	–	~ 3	~ 19	~ 9	~ 38
SAC_{254nm}, %	~ 22	~ 22	–	–	0	~ 21	0	~ 33
SAC_{436nm}, %	~ 63	~ 54	~ 55	~ 80	~ 19	~ 69	~ 21	~ 45
$PO_{4,total}$, %	~ 64	~ 76	–	–	~ 42	~ 79	~ 33	~ 90

mers constitute a threat for further treatment steps, such as reverse osmosis. Coagulant dosing prior SF reached a BIO-Polymer elimination rate of around 15%; coagulant dosing prior UF acquired approximately 79%.

3.4. Operational cost comparison

Comparison of all eight conditions cannot be based only on the stability of the permeability or the TMP, but also on overall operating expenditures (OPEX). Prices assumed for the calculation of reagents and power consumption are listed in Table 17 and OPEX calculation is presented in Table 18. Reagents considered were coagulant and those used for backwash and CIP but not those for CIP which is performed once a year and thus has a negligible effect on the reagent cost. Power calculation takes into consideration energy consumption for pumps (feed and backwash).

Comparing the continuous coagulant addition versus the intermittent addition, the major differences is the total operational costs. Due to the intermittent coagulant dosing for the first four minutes at the beginning of the filtration cycle, the costs for coagulants of this operation mode was around six times lower compared to operation with continuous coagulant dosing. Even though the CEB frequency of the test with continuous coagulant dosing could be lowered to e.g. once per day, the total operation costs will not be as low as of intermittent operation, because of the coagulant amount.

For the tests with chlorinated backwashes, the energy costs during operation with backwash at 50 mg/L CL_2 were higher, because of the higher TMPs. The lower chlorine dosing amount cannot neutralize this occurrence. It is necessary to decide if the amounts of needed chemicals or the energy costs are limited for the operation.

For the tests with sand filter, chemical costs are identical with similar coagulant dosage. Regarding energy cost, coagulant dosing upstream SF shows the lowest value but, as previously mentioned, the downsize is the blockage of the sand filter.

As a result and as shown in Fig. 15, lowest OPEX is achieved when ultrafiltration membranes are operated with chlorinated backwashes. The downsize of this solution being the formation of AOX compounds in the backwash waste water, the best solution is the operation with intermittent addition of coagulant upstream the UF with an OPEX roughly 3 to 6 times lower than the other conditions.

4. Conclusions

All conducted tests and examined processes showed stable operations at same operational parameter adjustments. The only differences were in TMP and permeability and the resulting operational costs, which were also influenced by the used amount of coagulant, chlorine and other chemicals.

One can conclude that it is not necessary to include a sand filter as a pretreatment upstream an ultrafiltration step for the treatment of tertiary waste water if the TSS concentration is within adequate range for the UF. If a sand filter is

Table 17
Prices used for OPEX calculation

Item	Price
Coagulant	73€-cent/kg
Acid	42€-cent/kg
Caustic	50€-cent/kg
Chlorine	52€-cent/kg
Power	12.9€-cent/kWh

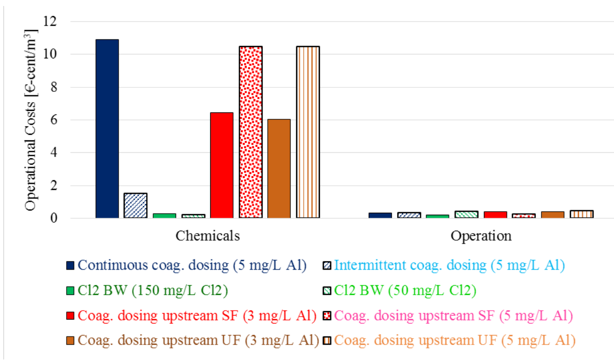

Fig. 15. OPEX Comparison.

Table 18
OPEX Calculation

Tests			Coagulant Dosage	Cl_2 dosage in BW	Chemicals	Operation	Total
			mg/L Al	mg/L Cl_2	€-cent/m³	€-cent/m³	€-cent/m³
I	Inline coag. dosing	Cont. coag. dosing	5	Nil	10.88	0.3	11.18
		Inter. coag. dosing	5	Nil	1.5	0.35	1.85
II	Chlorinated backwash	No coag. dosing	Nil	150	0.27	0.2	0.47
			Nil	50	0.23	0.44	0.67
III	With SF	Coag. dosing before SF	3	Nil	6.46	0.41	6.87
			5	Nil	10.47	0.27	10.74
		Coag. dosing before UF	3	Nil	6.04	0.41	6.45
			5	Nil	10.47	0.48	10.95

Coag.: Coagulant

already available, it is advisable to operate with coagulant dosing prior the UF, to avoid maybe higher CEB frequencies

With the aid of ultrafiltration, higher elimination rates of organic substances can be achieved compared to sand filtration. This fact was proofed with the special LCOCD analysis which was done for both tests: coagulant dosing prior SF and coagulant dosing prior UF.

If the use of coagulant is not possible or desired and the utilization of chlorine is not specified, it is demonstrated that operation with chlorinated backwashes and the same operational parameters is possible and could achieve comparable results.

The best solution regarding OPEX is the operation with intermittent addition of coagulant upstream the UF. The costs will roughly be 3 to 6 times lower compared to the other options.

References

[1] A. Angelakis, M. Marecos, L. Bontoux, T. Asano, The status of wastewater reuse practice in the mediterranean basin: need for guidelines, Water Res., 33(10) (1999) 2201–2217.

[2] C. Quist-Jensen, F. Macedonio, E. Drioli, Membrane technology for water production in agriculture: Desalination and wastewater reuse, Desalination, 364 (2015) 17–32.

[3] A. Peasey, U. Blumenthal, D. Mara, G.A. Ruiz-Palacios, Review of Policy and Standards for Wastewater Reuse in Agriculture: A Latin American Perspective. London School of Hygiene & Tropical Medicine. 2000.

[4] World Health Organization. Guidelines for the Safe Use of Wastewater, Excreta, and Greywater. Vol. 2, Wastewater Use in agriculture. Geneva, Switzerland. 2006.