ENVIRONMENTAL

On-site aerobic treatment at high and varying process water temperatures

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ABSTRACT– A two-stage (2 * 1 m^3) aerobic suspended carrier biofilm process (SCBP) was studied on mill premises for treatment of groundwood mill circulation water under high and varying process temperature. A rapid start-up was achieved with sludge from an existing mesophilic activated sludge plant treating mill wastewater. The two-stage SCBP produced 49%-77% GF50-filtered chemical oxygen demand (COD_{filt}) removals at volumetric loading rates of 3-14 kg COD_{filt} $m^{-3}d^{-1}$ and hydraulic retention times (HRTs) of 2-8 h, whereas the single reactor (first stage) produced 40%-67% COD_{filt} removals at loading rates of 7-28 kg COD_{filt} $m^{-3}d^{-1}$ and HRTs of 1-4 h. SCBP tolerated periodical temperature variations along with caustic shocks, and regained normal COD_{filt} removal within 24 h.

Keywords: thermophilic, suspended carrier biofilm process, aerobic, pulp and paper mill process water, varying temperature

APPLICATION– Pulp and paper mills looking to reduce their nominal water consumption can use a high-rate thermophilic aerobic biofilm process for internal treatment. Treatment reduces easily biodegradable matter.

INTRODUCTION

Many modern pulp and paper manufacturing processes generate high quantities of hot process waters and wastewaters, which are commonly treated in external aerobic wastewater treatment plants. Aerobic processes have been run so far exclusively under mesophilic conditions, i.e., at temperatures below 40°C. Thus, in many pulp and paper mills wastewaters are cooled before being subjected to mesophilic treatment. Besides as external wastewater treatment–aerobic treatment process operable at the prevailing high temperatures could be a preferable option as part of the internal treatment in closing water circuits in pulp and paper industries (Huuhilo *et al.* 2002). High temperature treatment would circumvent the cooling of the water making the treatment system technically simpler. Besides that operating under higher temperatures yields other benefits, like higher loading rates and lower net sludge yield. Biological wastewater treatment reduces effectively easily biodegradable matter, e.g., sugars, which can cause problems like slime formation in water circuits.

Only a few studies have been published on aerobic pulp and paper mill wastewater treatment under thermophilic conditions (reviewed by Jahren 1999, by LaPara and Alleman 1999, by Suvilampi *et al.* 2001, and by Vogelaar 2002). The studies, performed mainly in laboratory-scale, have shown stable removal of organic pollutants (measured as COD, for example) for thermophilic processes. Results are contradictory for the potential advantages and disadvantages – such as higher loading capacity, poorer sludge settling, and lower sludge yield–for thermophilic processes as compared to mesophilic processes. In the suspended carrier biofilm process (SCBP), an aerobic biological wastewater treatment system, biomass grows on carrier elements set in motion by aeration. SCBP has been shown to accommodate higher loadings and shorter hydraulic retention times (HRTs) than traditional aerobic systems, such as the activated sludge process (e.g., Ødegaard *et al.* 1994, Henze *et al.* 1997, Jahren 1999). The SCBP process is less sensitive to variation in process conditions and has been shown operable at 55°C in laboratory studies (e.g., Jahren 1999, Malmqvist 1999).

Laboratory-scale evaluation of internal aerobic thermophilic treatment of thermomechanical pulping whitewater in closed water circuits has been reported feasible with 10-fold water reuse (Jahren *et al.* 2000). Under mill conditions, the wastewater characteristics (organic composition and temperature) are subjected to variations that may greatly affect the performance of the process used. Laboratory-scale studies suggest that thermophilic processes tolerate lower temperatures, with rapid recovery or even increased removals (Barr *et al.* 1996, Suvilampi and Rintala 2002). High temperatures during mesophilic treatment, however, leads immediately to poorer process performance and effluent quality. Pilot-scale studies on mill premises are needed to determine the applicability of the process under actual mill conditions.

The objective of our study was to evaluate the feasibility of the pilot-scale aerobic SCBP under prevailing groundwood mill conditions (elevated and variable process water temperatures and varying water characteristics). GF/A-filtered COD (COD_{filt}) removal, effluent suspended solids (SS), and process resistance to caustic shocks and varying temperatures were selected to represent the process feasibility. We conducted two separate trials under various seasons on mill premises using pilot-scale reactors with groundwood mill circulation water (GWM) obtained from mechanical processing of wood.

MATERIALS AND METHODS

Wastewater

The GWM was obtained from the groundwood mill whitewater pipe system, a stream also containing varying amounts of whitewater from the paper machine. **Table I** presents the characteristics of the water after 1-mm pre-screening.

Experimental setup

Two serial aerobic reactors (referred to as R1 and R2 as single reactors and R12 as two-stage reactor) of total volume 2 m^3 were run in 37-day (referred to as trial I, from April to May 1999) and 63-day (trial II, from October to November 1999) trials. The reactors were filled to 50% of volume with carrier elements (Flootek RF 438) of density near water, which provided a total surface area of 190 m^2m^{-3} in both reactors. The RF 438 carriers, of length 36 mm and diameter 44 mm, are recycled polyethylene and have two internally crossed fins. The carriers had been used before and apparently contained some attached biomass. The pilot plant was a Floobed® unit (**Fig. 1**), where pH adjustment, temperature measurement, and nutrient addition were performed automatically. During start-up, microbial activity increase was detected before subjecting the wastewater into reactors. The increased microbial activity was detected by measuring dissolved oxygen (DO) level decrease in the reactors.

In reactor R1, we adjusted pH to 7.0 with 50% NaOH-solution, and added technical urea and phosphoric acid to maintain a COD:N:P ratio of 100:5:1 in trial I and 150:5:1 in trial II until day 37 and 150:4:1 thereafter. For trial I, we installed a 250-L lamella (also known parallel plate, Tchobanoglous and Burton, 1991) settling unit with sludge recirculation after the reactor stage; in trial II, neither sludge settling nor recirculation was applied.

A blower aerated the reactors to 3.0-4.0 mg O_2 L^{-1} of DO in R1. Manually controlled valves were used to maintain sufficient airflow in both reactors to keep the carriers moving. We took 24-h composite samples from the feed line after screening, effluent from R1, and final effluent after R2 were taken for analyzes.

Seed sludge

The reactors were inoculated in both trials with 55-60 L mixed liquor (40 L R1; 15-20 L R2; mixed liquor volatile suspended solids (MLVSS) 9-12 g L^{-1}) from the full-scale mesophilic activated sludge plant treating the wastewater from the pulp and paper mill. The inoculation temperatures were 50°C in R1 and 47°C in R2. The mixture of inoculum and wastewater was aerated for approximately 3 h until fresh wastewater was subjected to process.

Analyses

We analyzed suspended solids and volatile suspended solids (VSS) according to *Standard Methods* (APHA 1998). Attached total solids (TS-fix) were analyzed by weighing six to eight carriers after drying them at 105°C for 4 h, scraping off the bulk of the biomass, and brushing off the remainder in a soap solution. We weighed the carriers again after 4 h at 105° C. In both studies, the scraped biomass was used to determine VS/TS–ratio and to calculate volatile solids, VS-fix. Total VSS in the reactors was the sum of VSS and VS-fix. Sludge volume index (SVI) of the suspended biomass was measured from 30 min settled samples in 5-L graduated glass.

Dissolved organic carbon (DOC) was measured with a Shimadzu TOC-5050A Total Organic Carbon analyzer. We determined lignin and other aromatic compounds through ultraviolet absorbency at 280 nm (UV_{280}) according to Rintala and Lepistö (1992). Samples were diluted to an absorbency of less than 0.8. The amount of soluble lignin-like substances as SCOD was estimated with the absorbtivity coefficient of 22.3 L $g^{-1}cm^{-1}$ and the oxygen demand of 1.9 g O_2 g^{-1} lignin (Sierra-Alvarez *et al.* 1991). Sugars were determined with Anthron method. Total COD (COD_{tot}) and COD_{filt} were analyzed according to Finnish standard SFS 5504 (1988), GF/A-filtered biological oxygen demand (BOD_7) was analyzed according to SFS 3019 (1979). All the samples were GFA- or GF50-filtered (Schleicher and Schuell).

In the "Results" section, we present SCBP organic matter removal as COD_{filt} and DOC removals. All the volumetric loading and removal values are presented only as COD_{filt} to harmonize the results. A high correlation (r^2=0.98) between the DOC and COD_{filt} of the feed samples (feed COD_{filt} = 2.6 x DOC) was measured; hence the degree of accuracy is adequate.

RESULTS

The mesophilic sludge from the full-scale mesophilic activated sludge plant was used as inoculum. During batch-phase, the inoculum provided rapid (2-4 h) start-up, detected as DO-reduction in reactors. The GWM feeding was started immediately after lower DO levels were measured. COD_{filt} removal after 24-h operation was 47% and 22% after first stage (R1) and 53% and 44% after whole process (R12) in trials I and II, respectively.

Figures 2-4 show the performance of the serially connected aerobic reactors during the two trials. **Tables II-III** summarize the reactors' performance over a range of volumetric loading rates for non-disturbed operating periods when we analyzed additional parameters to characterize performance in more detail. In general, during both trials, HRTs were gradually lowered and volumetric loading rates increased (Figs. 2 and 3); loading rates also varied due to changes in feed COD_{filt}.

During both trials, HRTs were lowered to 1-1.6 h for R1 and 2-3.1 h for R12, corresponding to loading rates of about 20-28 and 10-14 kg COD_{filt} $m^{-3}d^{-1}$, respectively (Figs. 2 and 3, Tables II and III). For most of the trials, R1 removed 40% to 55% and R12 45 to 70% of DOC (Fig. 2). Increased loading rates and temperature variation between 39°C to 59°C had no perceptible effect on process performance as DOC removals. DOC removals were slightly lower during trial II than in trial I, with similar loading rates and hydraulic retention times. The highest removal rate during the two trials in R1 was 12.4 ± 0.5 kg $COD_{filt\ removed}$ $m^{-3}d^{-1}$, with an HRT of 1.4 h and loading rate of 28.3 ± 1.6 kg COD_{filt} $m^{-3}d^{-1}$, corresponding to 65 ± 3 g $COD_{filt\ removed}$ $m^{-2}d^{-1}$ (per carrier surface area) (Fig. 3) and to 40%-45% DOC removal. During that period, the sludge loading rate was as high as 20-25 kg COD_{filt} kg $VSS^{-1}d^{-1}$ (**Fig. 5**), with a substrate utilization rate of 9.1 ± 0.5 kg COD_{filt} kg $VSS^{-1}d^{-1}$ (Fig. 5). Sugars were removed by about 80% in R1 (Table III), whereas sugar removal in the second stage (R2) was insignificant (R12 removal was approximately matched R1 removal). Lignin-like COD removal for single reactor R1 and two-stage process R12 appeared to relate to the HRT (Tables II-III), although we found no statistical significance was found (data not shown). BOD_7 removals were up to 70%-80% in R12, versus 40%-65% in R1.

The concentration of attached biomass showed a gradual increase in the initial stages of both trials (Fig. 4). However, during both trials pH shocks led to some decreased values, especially in R1, whereas in R2 attached biomass remained unchanged or even increased irrespective of the pH shocks. During trial II, the concentration of attached biomass increased up to 4 kg VS-fix m^{-3} in R2, whereas much lower concentrations were measured in R1 throughout the trial. The non-attached biomass (free VSS) in the reactors accounted for 20% to 40% of the total VSS (free VSS+VS-fix) during both trials (data not shown).

During trial I the sludge settled poorly in the settling unit after the SCBP. The SVI of the returned sludge varied from 50 to 370 mL g^{-1} (average 140 ± 100 mL g^{-1}). Consequently, the actual amount of returned SS also ranged widely. Because of this, in trial II the sludge was not recycled. The average calculated sludge yields (as free VSS+VS-fix increase/COD removed) for first stage (R1) was 0.25 kg VSS kg COD_{filt}^{-1} and for two-stage process (R12) 0.15 kg VSS kg COD_{filt}^{-1} in trial II. Sludge yield was not determined in trial I because the sludge recycling was not operated in a stable manner. Yields showed high deviation calculated as daily values (Table III), typically the second stage had less effluent SS than effluent from R1 (influent to second stage) (Tables II-III).

During both trials, the processes experienced some unintentional process disturbances, due to mill upsets or the mechanical malfunctions in the pilot plant. These disturbances led to high pH values of up to 11-12 in R1, as follows: trial I; days 7-8, 24, and 30; trial II; days 24-25, 31, and 43. On days 24-25 and 31 in trial II pH failure was accompanied with aeration failures (DO 0 mg·L^{-1}). Duration of disturbances was 8-12 h for single days and approx. 20-30 h for two-day shocks. During the pH failures, DOC removal in R1 dropped to less than 20%. R2 maintained some DOC removal, as indicated by the lower decrease in DOC removals in R12 (Figs. 2 and 3). For example, in trial II a 12 h pH shock on day 25 (pH up to 12 in R1) combined with aeration failure reduced DOC removal to 30% in R12 (day 26) and led to an 11% increase in DOC in R1. Attached biomass was also washed out, as indicated by the reduction in biofilm concentration from 1.9 kg TS-fix m^{-3} to 0.5 kg TS-fix m^{-3} in R1 (day 29, Fig. 4).

DISCUSSION

The results obtained in this study show that biological aerobic SCBP treatment of pulp mill process waters is feasible and operable at high and varying temperatures. The reactor temperature occasionally ranged between 39°C and 59ºC without perceptibly affecting the performance of the reactor. A temperature tolerance was likely induced by thermotolerant microbial species and thermophiles present in the process (Tiirola *et al.* in press). The results also show that thermophilic SCBP can be rapidly started with inoculum from a mesophilic pulp and paper mill wastewater activated sludge plant. Thus, the present results would assist in developing new methods of operating existing external aerobic treatment systems and probably even in implementing biological internal treatment. However, thermophilic effluent had high turbidity and in trial I the sludge recycling was difficult due to floating sludge in the settling unit. The floating sludge was probably due to intensive aeration and high COD removal rates accompanied with high CO_2 concentrations in effluent, causing flotation and lifting the sludge in the settling unit. The high CO_2 release may occur in the high-rated process, with 5- to 10-fold COD removal rates compared to that of conventional aerobic wastewater treatment processes. In our study, poor settling was not of concern as the SCBP gave stable COD_{filt} removals, the process performance was not affected by sludge recycling, and the effluent quality was improved by subsequent screening (0.1 mm) and ultrafiltration unit (Huuhilo *et al.* 2000, Huuhilo *et al.* 2002.). The importance of immobilization of microorganisms is also suggested by the fact that the attached biomass on carrier elements was completely different from that in the suspension (Tiirola *et al.* in press).

The COD_{filt} removals and loading rates achieved in this study were comparable to those reported for similar type pulp and paper industry wastewaters in previous laboratory studies on thermophilic as well as mesophilic biofilm processes (**Table IV**). However, the potential for higher loadings in the thermophilic process is not evident in the table, nor can the thermophilic and mesophilic processes be directly compared, as only few comparative studies have been performed on them. In recent studies, thermophilic aerobic processes have shown lower COD_{filt} removals (Tripathi and Allen 1999, LaPara *et al.* 2001, Suvilampi and Rintala 2002, Vogelaar *et al.* 2002). They have also shown similar soluble COD (COD_{sol}) removals (Vogelaar *et al.* 2002, Suvilampi and Rintala 2002, Vogelaar *et al.* in press) than comparative processes under mesophilic conditions. The lower effluent quality in thermophilic processes with complex wastewaters, such as pulp and paper mill effluents may be due to the effect of influent colloidal material, the erosion of flocs, the increased complexity of wastewater substances, or the lower microbial diversity under higher temperatures (Tripathi and Allen 1999, LaPara *et al.* 2001, Vogelaar *et al.* 2002). With easily degradable wastewaters, the high density of free bacteria in the effluent may cause observed measured COD_{filt} removals (Suvilampi and Rintala 2002, Suvilampi *et al.* in press). However, it is obvious that post-treatment of thermophilic effluent by membrane technology yields better effluent quality than thermophilic biological unit alone.

High-rate process, accompanied with relatively small reactor size, is an attractive alternative when a pulp and paper mill is considering implementing a treatment process in mill premises. In thermophilic processes, increased microbial activity enables substrate utilization rates as high as 15.6 kg COD kg $VSS^{-1}d^{-1}$ (reviewed by Jahren 1999). In that study, a sludge load of 22 kg COD_{filt} kg $VSS^{-1}d^{-1}$ resulted in a maximum substrate utilization rate of 9.6 kg $COD_{filt\ removed}$ kg $VSS^{-1}d^{-1}$, which is markedly higher than the values reported for conventional aerobic processes (reviewed by Jahren 1999). The highest removal rate for the carrier surface area as 65 g COD_{filt} $m^{-2}d^{-1}$ under a loading rate of 148 g COD_{filt} $m^{-2}d^{-1}$ was attained during trials. Maximum removal rates of 95 (Jahren and Ødegaard 1999), 48 (Rusten *et al.* 1999), and 25-30 g COD_{filt} $m^{-2}d^{-1}$ (Ødegaard *et al.* 2000) have been reported for a laboratory-scale 55°C moving bed biofilm reactor (MBBR) treating high strength wastewater (diluted molasses), a pilot-scale mesophilic (34°C) MBBR treating mixed chemical plant wastewater, and low-temperature (10°C -15°C) MBBR treating synthetic wastewater, respectively.

The two-stage SCBP tolerated the different operational conditions and disturbances well even under thermophilic conditions. The operation of a 55°C SCBP with 70% to 90% COD_{filt} removals has been reported even at a pH of 3.2 to 4.5 (Malmqvist *et al.* 1999). In our study, COD_{filt} removals in R1 recovered rapidly (in 1-3 days) after a 2-day, high pH shock (pH 10-11), even without reduced loading rates. The shocks decreased DOC removals in R1 while those in R2 increased, resulting in only slightly decreased efficiency in R12. No washout of the attached biomass in the latter reactor was measured during disturbed operation. The latter reactor thus apparently greatly stabilized the process, suggesting that two-stage biological treatment is capable of producing steady COD_{filt} removals under varying operating conditions.

Compared to mesophilic processes, thermophilic processes are claimed to have a low sludge yield (LaPara and Alleman 1999), though the values reported for aerobic thermophilic processes vary greatly (reviewed by Jahren 1999 and LaPara and Alleman 1999, see also e.g. Becker *et al.* 1999 and Bérubé and Hall 2000). While values evidently do vary in different cases because of different wastewater characteristics and operational conditions, such variation does not clearly argue for the effect of temperature on sludge yield. Operation and follow-up for longer periods than in our study is no doubt required to collect reliable information on sludge production for full-scale estimates.

The approximately 10% higher removal of COD_{filt} in trial I (trial performed in autumn) than in trial II (trial performed in spring) may be attributable to seasonal variation in the characterization of spruce feedstock used in pulping composition. The biodegradable COD in trials I and II was 77% and 68%, respectively (measured as highest removal rate). On the other hand, a higher proportion of sugars, lignans, sterols, steryl esters, and triglyserides were removed in trial II than in trial I (Huuhilo *et al.* 2000, Huuhilo *et al.* 2002.).

In this study we periodically observed a reddish color in treated wastewater, but no clear reason for this was found. The formation of a reddish-brownish color during aerobic treatment of anaerobically pretreated thermomechanical pulp mill waters has been observed previously in mesophilic processes, whereas this did not occur during direct aerobic treatment (Rintala and Vuoriranta 1988). Field and Lettinga (1989) suggested that the reddish color relates to oxidation of phenolic compounds. However, color can be reduced by ultrafiltration and/or nanofiltration (Nuortila-Jokinen *et al.* 1996, Huuhilo *et al.* 2002).

CONCLUSIONS

Our study showed that the aerobic suspended carrier biofilm process is feasible to cut 40%-60% of COD_{filt} at high and varying temperatures (39°C-59°C) and that sludge from an existing full-scale mesophilic activated plant may be used successfully to start operation at a high temperature. COD_{filt} removals of 49%-77% were attained with loadings of 3 to 15 kg COD_{filt} $m^{-3}d^{-1}$ (corresponding to HRT 2-8 h) and removals of 40% with loadings up to 22-30 kg COD_{filt} $m^{-3}d^{-1}$ (HRT 1-1.6 h).

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Insights from the authors

Q: Why did you choose this topic to research?
A: Research was initiated during the CACTUS-project, which focused on minimizing the nominal water consumption in paper making process. This project resulted as my personal 4-year study of thermophilic aerobic wastewater treatment.

Q: How does this research either compliment and support previous research you (or others) have done or how does it differ from previous research.
A: This was one the first pilot studies conducted in mill premised. The original purpose was to conduct a feasibility study, however, due to the nature of pilot-scale, also varying temperature as found interesting.

Q: What was the most difficult aspect of this research and how did you address that?
A: Sludge recycling due to the poor thermophilic sludge settling properties. This led to the operation of the process without sludge recycling and it was found that process had similar efficiency with or without sludge recycling (this is mainly because most of the biomass is attached on the carrier surface).

Q: What did you personally discover from this research? What was most interesting or surprising about your findings?
A: I found that biology in the wastewater treatment is not so critical to the environmental conditions as believed and that the suspended carrier biofilm process was robust and efficient. Later this lead to changing my focus to more vulnerable process, i.e. activated sludge process, which is much more reliable on the sludge settling properties.

Q: How might mills benefit from or use this information?
A: The mill operators can see that the biological wastewater treatment is feasible in mill premises and that it's a robust process also rather simple

Q: What's the next step?
A: Some mills have already taken the first step by implementing the thermophilic treatment in mill-scale. However, as internal treatment, those processes are mainly membrane bioreactors and not suspended carrier biofilm processes, which I would like to see commissioned with proper post-treatment (flotation and/or membrane filtration) in some mill process water cycle.

Parameter	Trial I				Trial II			
	N	Average	Min	Max	N	Average	Min	Max
Temperature, °C	81	60 ± 5	38	68	55	62 ± 3	52	70
SS, mg L^{-1}	18	460 ± 270	250	1300	22	170 ± 40	120	270
VSS, mg L^{-1}	18	440 ± 260	230	1270	22	150 ± 20	110	190
DOC, mg L^{-1}	32	430 ± 90	250	600	42	500 ± 80	350	720
COD_{tot} mg L^{-1}	9	1300 ± 260	800	1600		nd.		
COD_{filt}, mg L^{-1}	9	1100 ± 250	690	1500	11	1430 ± 170	1100	1750
BOD_7, mg L^{-1}	9	650 ± 140	430	900	6	770 ± 80	740	870
Lignin-like compounds, COD mg L^{-1}	6	340 ± 56	270	400	6	410 ± 35	360	440
Sugars, COD mg L^{-1}		nd.			6	330 ± 50	285	405

N = number of samples, nd. = not determined

I. Characteristics of groundwood mill circulation water used as feed in two pilot trials.

			Reactor R1	Reactor R12	Reactor R1	Reactor R12
Parameter	Unit	Days	17 – 21		35 - 37	
Temperature	°C		52.5 ± 0.7		54 ± 1	
Loading rate	kg COD_{filt} $m^{-3}d^{-1}$		7.6 ± 1.6	3.8 ± 0.8	20.5 ± 2.3	10.3 ± 1.2
Sludge load	kg COD_{filt} kg $VSS^{-1}d^{-1}$		3.0 ± 1.4	1.4 ± 0.4	11.2 ± 2.3	3.8 ± 0.5
HRT	h		3.3 ± 0.0	6.7 ± 0.0	1.6 ± 0.1	3.1 ± 0.0
Removal rate	kg COD_{filt} $m^{-3}d^{-1}$		4.4 ± 0.1	2.7 ± 0.3	9.7 ± 1.3	6.2 ± 1.0
DOC removal	%		55 ± 6	70 ± 6	45 ± 2	57 ± 3
COD_{filt} removal	%		59 ± 11	72 ± 7	47 ± 1	60 ± 3
COD_{tot} removal	%		53 ± 7	64 ± 3	42 ± 2	50 ± 0
BOD_7 removal	%		64 ± 9	89 ± 4	57 ± 2	72 ± 1
UV_{280} removal	%		26 ± 17	36 ± 17	-[a]	8[b]
Effluent SS	g L^{-1}		0.76 ± 0.18	0.48 ± 0.12	0.69 ± 0.07	0.66 ± 0.14

[a]negative value, [b]data from one day only, nd. not determined

II. Aerobic suspended carrier biofilm process performance in trial I (average ± standard deviation) under different loading rates in single reactor (R1) and in two-stage reactor (R12).

			Reactor R1	Reactor R12	Reactor R1	Reactor R12	Reactor R1	Reactor R12
Parameter	Unit	Days	11-13		53-55		61-63	
Temperature	°C		55 ± 0.4	53 ± 1.7	55 ± 0.9	54 ± 0.5	55 ± 0.9	54 ± 0.5
Loading rate	kg $COD_{filt} \cdot m^{-3}d^{-1}$		13.3 ± 1.8	6.6 ± 0.9	27.4 ± 2.0	13.7 ± 1.0	27.4 ± 0.2	13.7 ± 0.1
Sludge load	kg COD_{filt} kg $VSS^{-1}d^{-1}$		8.1 ± 2.1	2.8 ± 0.4	19.6 ± 3.1	4.6 ± 0.5	15.6 ± 0.1	4.3 ± 0.0
HRT	h		2.4 ± 0	4.8 ± 0	1.45 ± 0	2.9 ± 0	1 ± 0	2 ± 0
Removal rate	kg COD_{filt} $m^{-3}d^{-1}$		6.7 ± 1.1	4.2 ± 0.7	11.3 ± 06	8.3 ± 0.6	11.3 ± 0.5	8.0 ± 0.2
DOC removal	%		51 ± 4	62 ± 3	41 ± 4	60 ± 1	41 ± 2	58 ± 2
COD removal	%		49 ± 4	65 ± 3	36 ± 3	55 ± 2	nd.	nd.
BOD_7 removal	%		68 ± 5	80 ± 3	45 ± 2	76 ± 1	nd.	nd.
UV_{280} removal	%		13 ± 3	35 ± 4	9 ± 8	7 ± 8	nd.	nd.
Sugars removal	%		82 ± 5	88 ± 2	76 ± 8	82 ± 24	nd.	nd.
Effluent NH_4-N	mg L^{-1}		31 ± 13[a]	30 ± 11[a]	5.4 ± 2.9[b]	1.2 ± 1.3[b]	nd.	nd.
Efflluent SS	g L^{-1}		0.32 ± 0.01	0.28 ± 0.06	0.34 ± 0.03	0.37 ± 0.04	0.37[a]	0.22[a]
Sludge yield	kg VSS kg $COD_{filt\ removed}^{-1}$		0.21 ± 0.04	0.16 ± 0.12	0.21 ± 0.01	0.09 ± 0.09	0.53[a]	0.14[a]

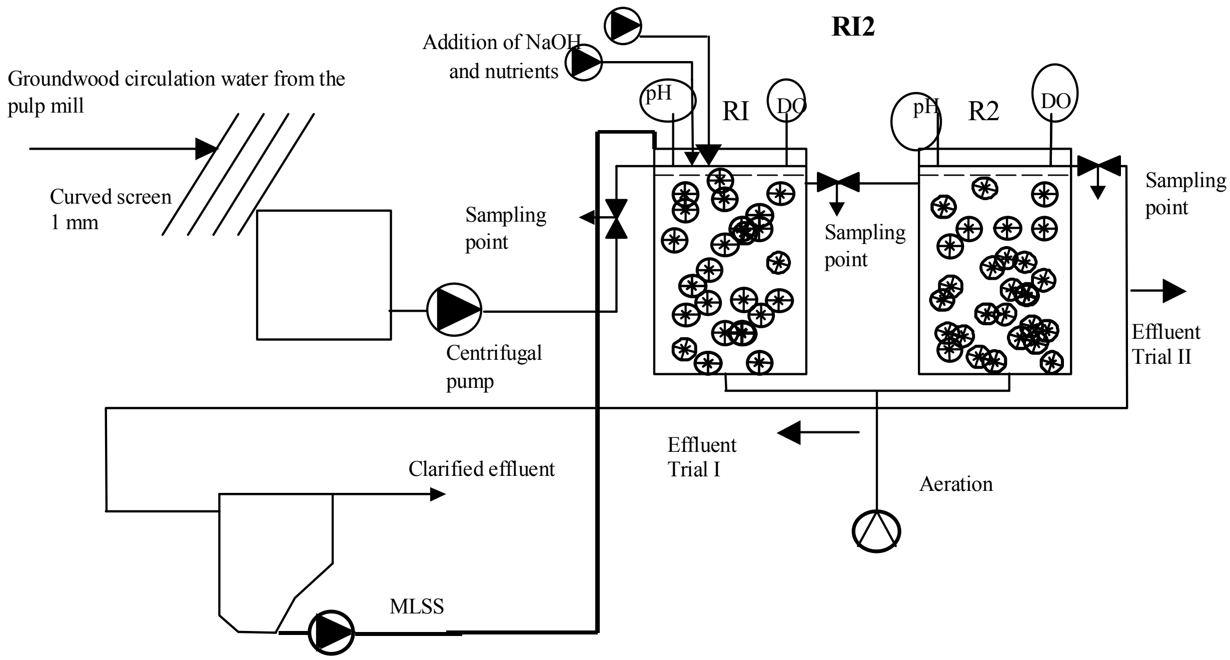
[a] data from one day only, nd. not determined

III. Aerobic suspended carrier biofilm process performance in trial II (average ± standard deviation) under different loading rates in single reactor (R1) and in two-stage reactor (R12).

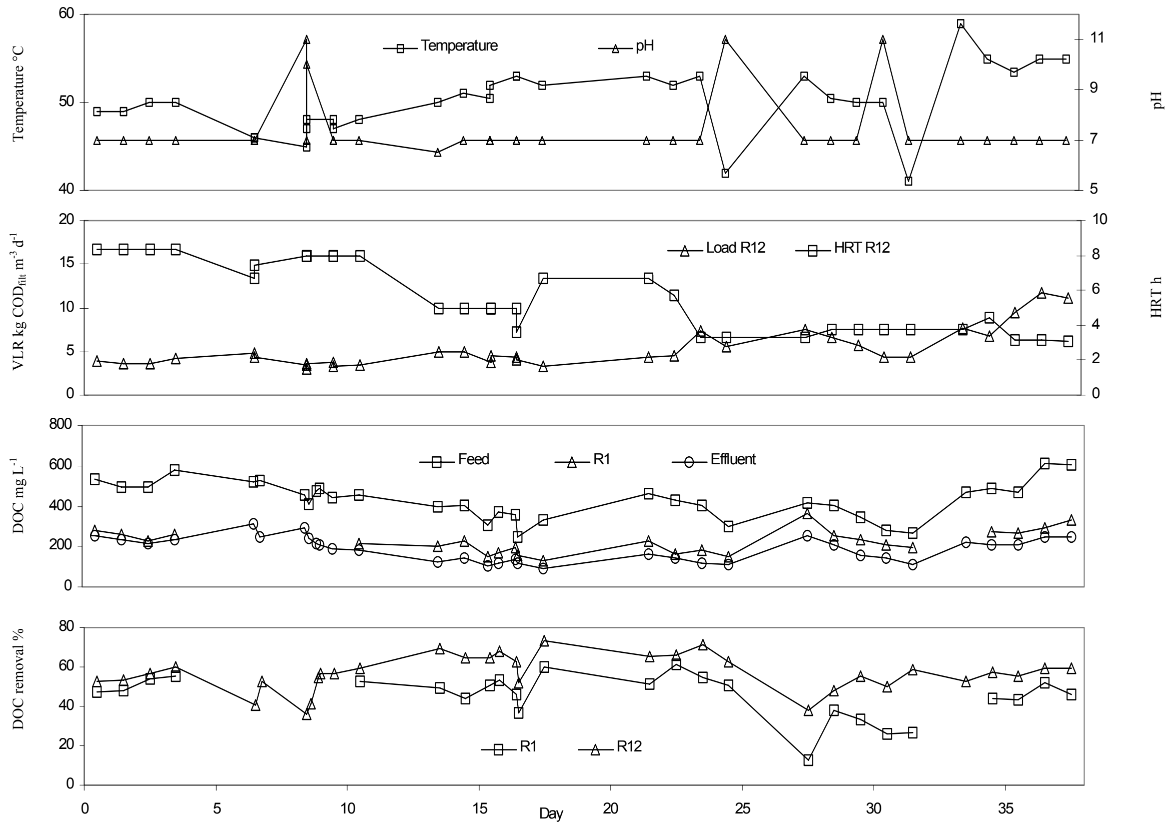
Process	T ºC	Scale	Wastewater	Loading rate kg CODm^{-3}d^{-1}	Sludge load kg COD kg VSS^{-1}d^{-1}	HRT h	COD removal %	Reference
BF	meso	pilot	Neutral paper mill effluent	1-10	nr.	0.3-0.65	30-91	Kantardjieff and Jones 1997
MBBR	29-35	pilot	Thermomechanical GW	7.6-17.8	nr.	4-10	75-78	Broch-Due *et al.* 1997
MBBR	28	pilot	Secondary fiber mill	25 [a]	nr.	1.3	40-50	Dalentoft and Thulin 1997
MBR	55	lab	TMP whitewater	5	0.45	17	77	Tardif and Hall 1996
AS	41-50	lab	bleached kraft	2.8-8.4	nr.	4-12	29-48	Barr *et al.* 1996
MBR	55	lab	TMP whitewater	4.1-12.4[a]	nr.	8-24	35-45	Ragona and Hall 1998
MBBR	55	lab	TMP whitewater	2.5-3.5	1.5-2.6	13-22	60-65	Jahren *et al.* 2002
MBBR	55	lab	TMP whitewater	1.6-12	0.8-6.2	8-24	15-55	Jahren and Ødegaard, 1999
SCBP	40-50	full	CTMP effluent	100	nr.	1	15-25	Malmqvist *et al.* 1996
SCBP	50-52	lab	Liner	nr.	nr.	10-13	86-90	Malmqvist *et al.* 1999
SCBP^{R1}	39-59	pilot	GWM	6.5-30	2.0-24	1-4.5	40-67	Present study
SCBP^{R12}	39-59	pilot	GWM	3.2-15	1.1-5.2	2-9	49-77	Present study

[a]Calculated from reported feed COD and HRT, AS = Activated Sludge, BF = Aerobic Biofilter, CMTP = chemithermomechanical pulp, GW = groundwood pulp, GWM = groundwood mill water, MBR = Membrane Bioreactor, MBBR = Moving Bed Biofilm Reactor, meso = mesophilic, SCBP = Suspended Carrier Biofilm Process, TMP = thermomechanical pulp, feed COD 800-3500 mg·L^{-1} except in study from Kantanrdjieff and Jones (1997); feed COD 57-550 mg L^{-1}. nr. = not reported.

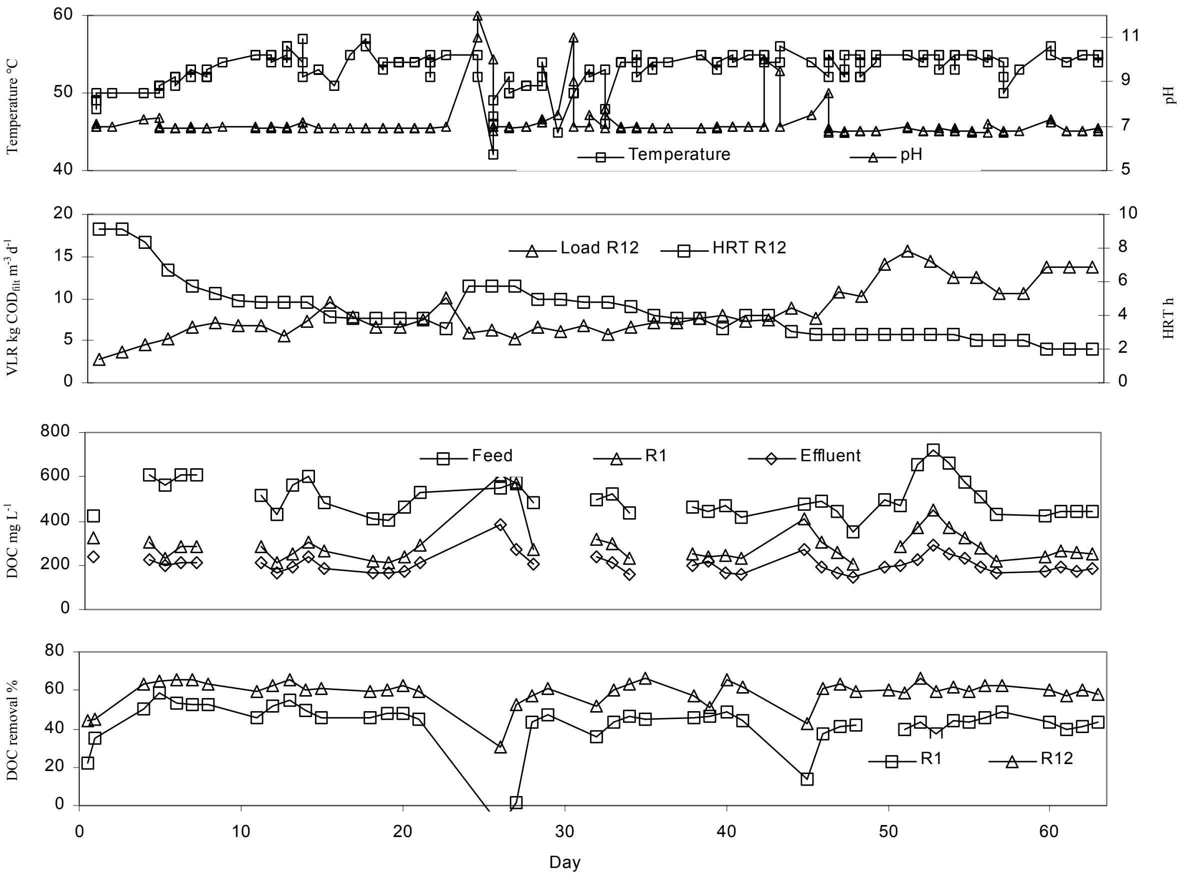
IV. Thermophilic aerobic treatment of pulp and paper mill wastewaters, with some biofilm process performances under mesophilic conditions for reference.



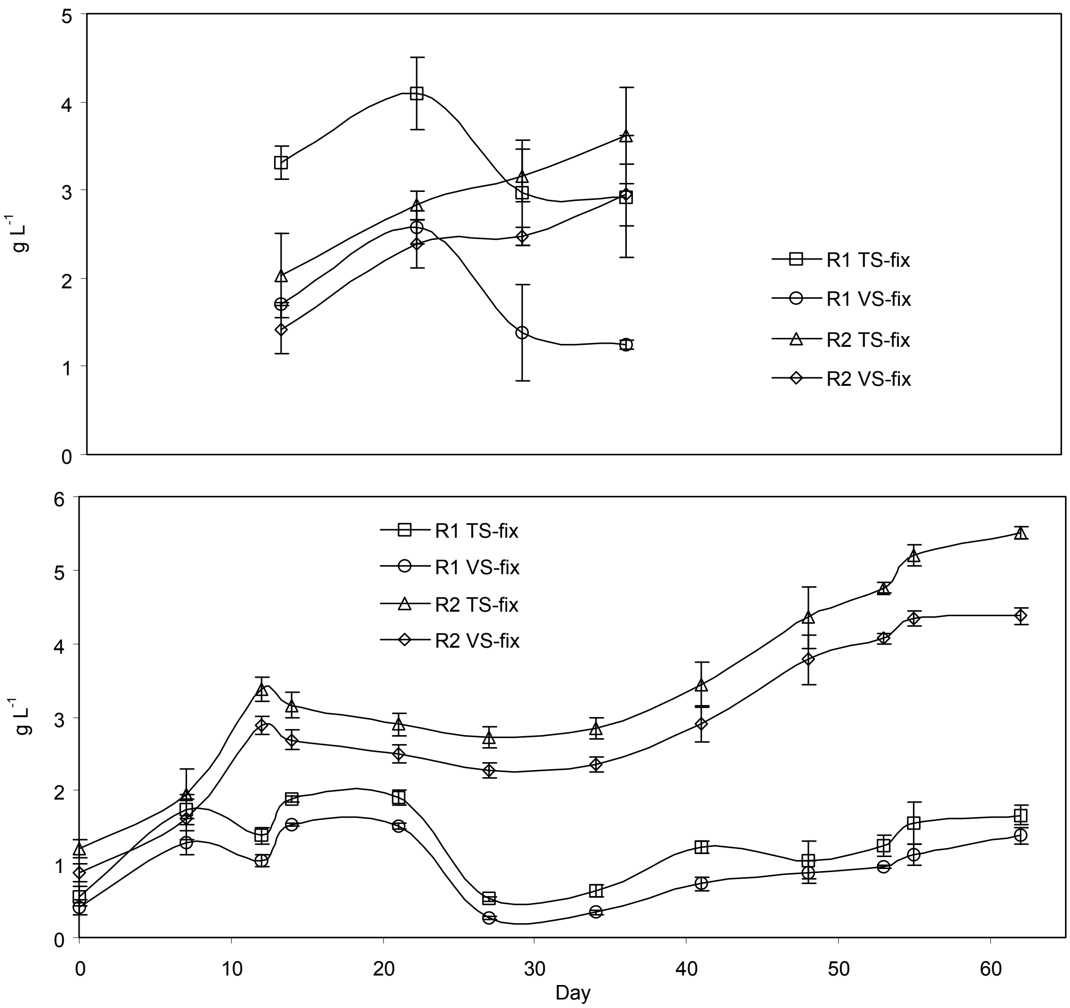
1. Schematic presentation of pilot set-up



2. Temperature, pH, volumetric loading rate (VLR), HRT (R12), DOC removals (R1 and R12), DOC (feed, after R1, and after R2) in aerobic suspended carrier biofilm process during pilot trial I. R1 VLR and HRT are not presented in figure, VLR for R1 was twice the figure than for R12, and HRT was half the figure for R1 than for R12.



3. Temperature, pH, volumetric loading rate (VLR), HRT R12, DOC removals (R1 and R12), DOC (feed, after R1, and after R2) in aerobic suspended carrier biofilm process during pilot trial II. R1 VLR and HRT are not presented in figure, VLR for R1 was twice the figure than for R12, and HRT was half the figure for R1 than for R12.



4. Attached biomass (TS-fix and VS-fix) in aerobic suspended carrier biofilm process during pilot trials I (above) and II (below).