PILOTING AN MBBR TO TREAT POND EFFLUENT FOR NITROGEN REMOVAL

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ABSTRACT (500 WORDS MAXIMUM)

Oxidation pond-based wastewater treatment plants (WWTPs) are common across New Zealand. Many pond-based WWTPs in New Zealand inconsistently meet compliance requirements for nutrients based on several factors including retention time, pollutant loading, aeration intensity, temperature etc. As effluent nutrient loading becomes a greater focus across New Zealand environments, the expectations are for resource consent requirements on nutrient discharge to become significantly more stringent. This will make the feasibility of using oxidation pond-based treatment plants to meet resource consent requirements in the future a higher risk proposition. To address this risk, significant investment in these oxidation pond-based WWTPs is necessary.

Moving bed biofilm reactors (MBBR) provide a reliable technical solution to remove nitrogen from wastewater. Use of MBBR technology is established and widespread outside of New Zealand, but there are only a handful of full-scale installations within New Zealand. The MBBR technology is a cost-effective, low footprint treatment process, which can be used in combination with existing pond-based systems as a bolt-on augmentation for effective nitrogen removal at treatment plants.

The paper introduces the MBBR process basics. It discusses the design, configuration and performance of a two-stage pilot plant that treated wastewater from a municipal pond system for total nitrogen removal using acetic acid as the exogenous carbon source. The pilot trial went from 12 April to 5 August 2022, for a total of 114 days.

The plant operated during winter temperatures between 10 and 13°C. It was able to remove total ammoniacal nitrogen (TAN) and nitrate concentrations to below 1 mg/L. The measured empirical surface area removal rates (SARR) were comparable to expected theoretical design values.

KEYWORDS

Wastewater treatment, moving bed biofilm reactor, MBBR, nitrogen removal, nutrient removal, oxidation pond upgrade

PRESENTER PROFILE

Andreas is the Innovation Lead and a Senior Process Engineer at Lutra. He has 11 years of experience in municipal drinking water and wastewater treatment. He was involved in designing, project managing and commissioning of works on existing and new treatment plants.

NOMENCLATURE

Abbreviation	Description
BOD5	Biological oxygen demand in 5 days
COD	Chemical oxygen demand
MBBR	Moving bed biofilm reactor
NO_x	Nitrite (NO_2^-) and nitrate (NO_3^-)
NO_x-N_{eq}	NO_x-$N_{equivalent}$, NO_x plus nitrate equivalent of dissolved oxygen
SARR	Surface area removal rate (g per m^2 carrier media surface area per day)
TAN	Total ammoniacal nitrogen, includes both ammonia (NH_3) and ammonium (NH_4^+)
VRR	Volumetric removal rate (g per L carrier media per day)

INTRODUCTION

Oxidation pond-based wastewater treatment plants (WWTPs) are common across New Zealand. Many pond-based WWTPs in New Zealand inconsistently meet compliance requirements for nutrients based on several factors including retention time, pollutant loading, aeration intensity, etc. As effluent nutrient loading becomes a greater focus across New Zealand environments, the expectations are for resource consent requirements on nutrient discharge to become significantly more stringent. This will make the feasibility of using oxidation pond-based treatment plants to meet resource consent requirements in the future a higher risk proposition. To address this risk, significant investment in these oxidation pond-based WWTPs is necessary.

Historically there have been several approaches taken to increase nutrient removal in oxidation ponds such as rock beds, AquaMats, and other fixed film technologies. Recently a few new technologies have been introduced in New Zealand including BioBloks, membrane aerated biofilm reactors (MABR), and moving bed biofilm reactors (MBBR).

Of these three newer technologies, MBBR has a long track record for nutrient removal as the technology has over 30 years of use with thousands of installations worldwide. MBBR provides a reliable, compact, well proven, and cost-effective technical solution to remove nitrogen from wastewater as a bolt on solution to existing oxidation ponds. Use of MBBR technology is established and widespread outside of New Zealand, but there are only a handful of full-scale installations within New Zealand.

MBBR TECHNOLOGY

The MBBR technology utilises free floating high density polyethylene carrier media for biofilm attachment and pollutant removal. The media is retained in reactors with perforated retention screens installed on the reactor outlet. MBBR can provide treatment in aerobic applications for removal of soluble BOD and nitrification, or anoxic applications for denitrification using native carbon in the influent or exogenous carbon in the form of methanol, acetic acid, etc.

The MBBR technology originated in Scandinavia in the late 1980's and has been used effectively for municipal and industrial applications throughout the world. MBBR reactors typically have a short HRT (20-60 minutes) and operate well at low temperatures with good resilience to toxic substances and shock loads. The MBBR technology was implemented in the Wellington region at the Moa Point WWTP and Western WWTP for high-rate BOD removal upstream of a high-rate conventional activated sludge system operating at a short SRT. Aside from that, there are few MBBR's in operation throughout New Zealand.

MBBR PILOT TRIAL

To help socialise the MBBR technology in New Zealand with the technology, Lutra built an MBBR pilot plant. At the time of writing of this paper, Lutra has concluded a trial with one organisation where the pilot plant treated municipal wastewater from an oxidation pond. The trial took place from 12 April 2022 to 5 August 2022, for a total of 115 days. A trial with another organisation will start at the end of August 2022.

OBJECTIVES OF THE PILOT TRIAL

Trial objectives can differ depending on the existing treatment plant and the final effluent quality that each organisation needs to achieve. In general terms, the objectives of the pilot study are outlined below:

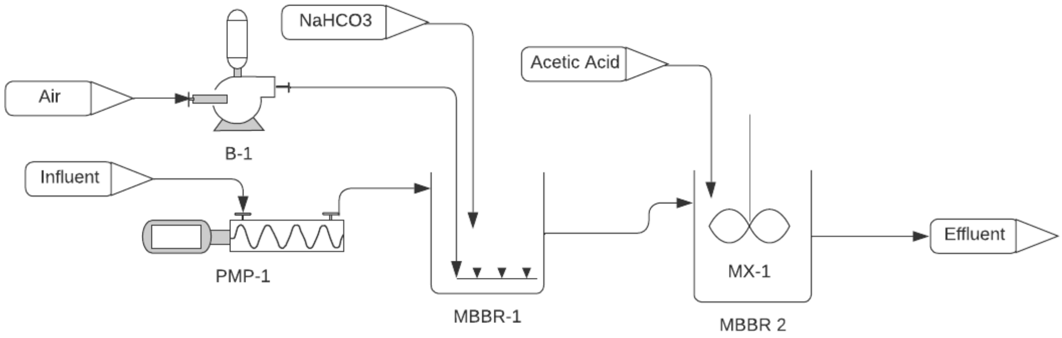
- Establish typical and maximum nitrogen removal rates (which translate into removal loads) while achieving low effluent ammonia and nitrate concentrations (but not necessarily below 1 mg N/L)
- Treat wastewater to an effluent ammonia concentration of below 1 mg N/L
- Treat wastewater to an effluent nitrate and nitrite (NO_x) concentration of below 1 mg N/L

MATERIALS AND METHODS

PILOT PLANT SETUP

The pilot plant consists of two tanks. In the first stage (tank one), ammonia is converted to nitrate (nitrification). In the second stage (tank two), the nitrate is converted to nitrogen gas (denitrification) using acetic acid as the exogenous carbon source. A progressive cavity pump operating on a VSD delivered oxidation pond effluent to the plant. The treated effluent returned to the same oxidation pond via gravity flow. A fixed speed blower fed an air grid in the first stage. An exhaust valve controlled the amount of air going into the air grid. The second stage was mixed by a variable speed mixer.

Figure 1: Simplified process flow diagram of the pilot plant



The process design of the pilot is provided in the following table:

Table 1: Pilot plant design parameters

Parameter	Unit	Stage 1	Stage 2
Tank Liquid Volume	L	230	230
Media Volume	L	90.5	93
Media % Fill	%	~40	~40
Media Type	-	BioChip 30	K1 equivalent
Side Channel Blower Motor Size	kW	1.1	N/A
Mixer Motor Size	W	N/A	80
Operating Mixer Speed	Hz	N/A	37

The pilot skid is shown in the photographs below:

Figure 2: Pilot skid as installed onsite

Mutag BioChip 30 is the media type used for the first stage. The manufacturer claims up to 5,000 m^2 of surface area per m^3 of media. A secondary objective of this trial was to estimate the effective surface area of this media type. The second stage carrier media is a conventional media design based on the AnoxKaldnes K1 with an approximate effective surface area of 500 m^2 per m^3.

Figure 3: MBBR media types used in the study – Mutag BioChip 30(L) and K1 equivalent (R)

To reduce cost, the plant does not have remote telemetry capabilities or flow switches that control pump inputs. For example, a no feed flow event does not automatically stop the two chemical dosing pumps. After a power outage, the blower, mixer and dosing pumps restart automatically. The feed pump initially did not but was re-programmed later to restart as well.

The adjustable operational parameters are feed flow, first stage aeration rate (DO), first stage alkalinity, second stage acetic acid dose, and second stage mixer speed.

CHEMICAL DOSING

Two chemical dosing pumps added two chemicals to the pilot plant. An 80 g/L baking soda (sodium bicarbonate, $NaHCO_3$) solution added alkalinity to the nitrification (first) stage. A 10% w/w acetic acid solution added readily biodegradable COD to the denitrification (second) stage.

During the trial period, the pilot plant was visited once to twice per week. Chemical dosing was set at fixed flows locally at the chemical feed pumps and were adjusted throughout the trial based on reactor influent lab results and projected loading rates. Alkalinity was adjusted to maintain an effluent concentration between 80-100 mg/L as $CaCO_3$. The acetic acid dosing was set to maintain a slight overdose based on Stage 1 effluent NO_x-N and DO concentrations.

MBBR KINETICS

A critical design and performance parameter for MBBR is the surface area removal rate (SARR) quantified in grams of pollutant removal per m^2 of carrier media per day or g/m^2/d. Typically the SARR is impacted by substrate concentrations such as DO and TAN for nitrification, and nitrate and available carbon for denitrification. Environmental conditions, most notably wastewater temperature, will also have a significant impact on SARR.

Throughout this paper, all nitrogen measurements are given "as Nitrogen", i.e. TAN, NO_3-N, NO_2-N, NO_x-N, NO_x-N_{eq}.

The observed SARR is calculated by dividing the load of pollutant removed by the known surface area, such as shown in equation (1):

$$(1)\ SARR = \frac{Q(C_{in} - C_{out})}{Carrier\ media\ volume \times Specific\ surface\ area}$$

SARR: surface area removal rate ($g/m^2/d$)
Q: flow (m^3/h)
C_{in}: concentration of TAN or NO_x-N or NO_x-N_{eq} into the reactor (g/m^3)
C_{out}: concentration of TAN or NO_x-N or NO_x-N_{eq} out of the reactor (g/m^3)
Carrier media volume: within reactor (m^3)
Specific surface area: of the carrier media (m^2/m^3)

NO_x-N_{eq} is used to quantify the overall load for the denitrification stage. It is calculated as per equation (2):

$$(2)\ NO_x - N_{eq} = NO_3 - N + 0.6 \times NO_2 - N + 0.35 \times DO$$

NO_x-N_{eq} (mg/L)
NO_2-N: Nitrite concentration (mg/L)
NO_3-N: Nitrate concentration (mg/L)
DO: dissolved oxygen concentration (mg/L)

LABORATORY SAMPLING

Sampling and analysis was undertaken by an external laboratory (Eurofins). The turn-around time between sampling and results was a minimum of one week.

Measured parameters are listed in *Table* 2. Samples were taken three times per week. Influent samples were collected from the oxidation pond at the location of the feed hose. First stage samples were taken from the drain valve, with the first flush discarded. Second stage samples were taken from the outlet of the effluent hose. For DO measurements, a handheld device was immersed in the tanks.

Table 2: Measured parameters and their measuring location during the trial. Parameters with (*) were measured three times per week, (#) twice per week, and the others weekly.

Parameter	**In**	**1st**	**2nd**	**Parameter**	**In**	**1st**	**2nd**
TAN (*)	X	X	X	$CBOD_5$	X		X
Nitrate (*)	X	X	X	Soluble $CBOD_5$ (#)	X		
Nitrite (*)	X	X	X	COD (*)	X		X
Total Kjeldahl nitrogen	X		X	Total suspended solids	X		X
Total alkalinity (*)	X	X		Total phosphorus	X		X
pH (*)	X	X	X	Dissolved reactive phosphorus	X		X
Temperature (*)	X	X	X	Dissolved oxygen		X	X

PILOT EXECUTION

EVENTS

Table 3 presents a timeline of significant events during the trial. It includes feed flow changes but does not detail adjustments to the chemical dosing pumps.

While pre-trial oxidation pond sample results indicated just enough alkalinity to sustain the nitrification reaction, the actual concentration when the trial started was too low (around 75 mg/L as $CaCO_3$ in the influent, see Figure 6). As a result, the performance of both first and second stage was poor. Performance improved significantly after additional alkalinity was added into the first stage, on 23 May 2022 (41 days after start of trial).

Judging by the results, stable operating conditions were achieved between 28 May and 26 June (called “period 1”), and 21 July until 5 Aug 2022 (called “period 2”). These periods are shaded green in some result figures.

Table 3: Timeline of events (all dates in 2022)

Date	Description
12 April	Installation of pilot plant. Initial flow rate was 7.2 L/min.
7 May	Process upset – some loss of performance. After a regional power outage, all equipment except the feed pump restarted. Plant operated for two days without feed flow, but with acetic acid dose into the second stage.
13 May	Flow increased to 10.1 L/min to increase TAN and NOx-N load.
23 May	Installation of alkalinity dosing to the first stage. The feed pump VSD controller was changed to restart automatically after a power cut.
27 June	Process upset - nitrifying activity was completely lost and it took 23 days to recover. It is assumed the nitrifier die-off was caused by a high pH in the first stage. The cause of upset was that the feed pump was found not operating, and could have potentially been not operating for up to two days. All other equipment was operating, including the chemical dosing pumps which dosed into the stagnant tanks.
8 July	Feed pump flow was reduced to 5.6 L/min.
1 August	Feed pump flow was increased to 8.2 L/min.
5 August	End of pilot trial.

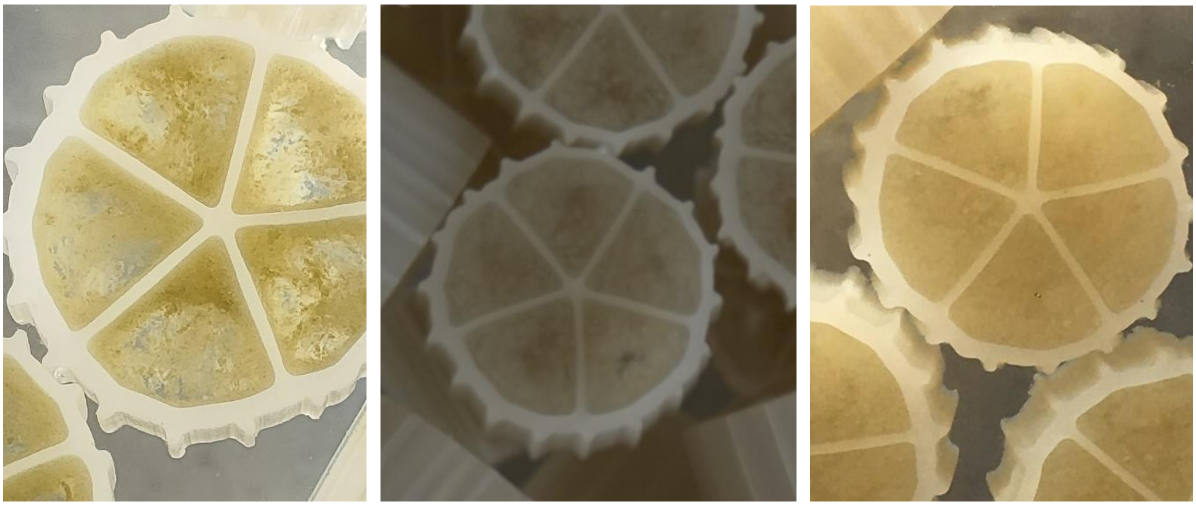
BIOFILM DEVELOPMENT

A progression of media appearance with varying biofilm growth is presented in *Figure 4* and *Figure 5*.

Figure 4: First stage media during the trial. (b) is during the process upset where no nitrifying activity was observed. At (c) nitrification was operating again.

(a) 31 days (b) 88 days (c) 106 days

Figure 5: Second stage media during the trial

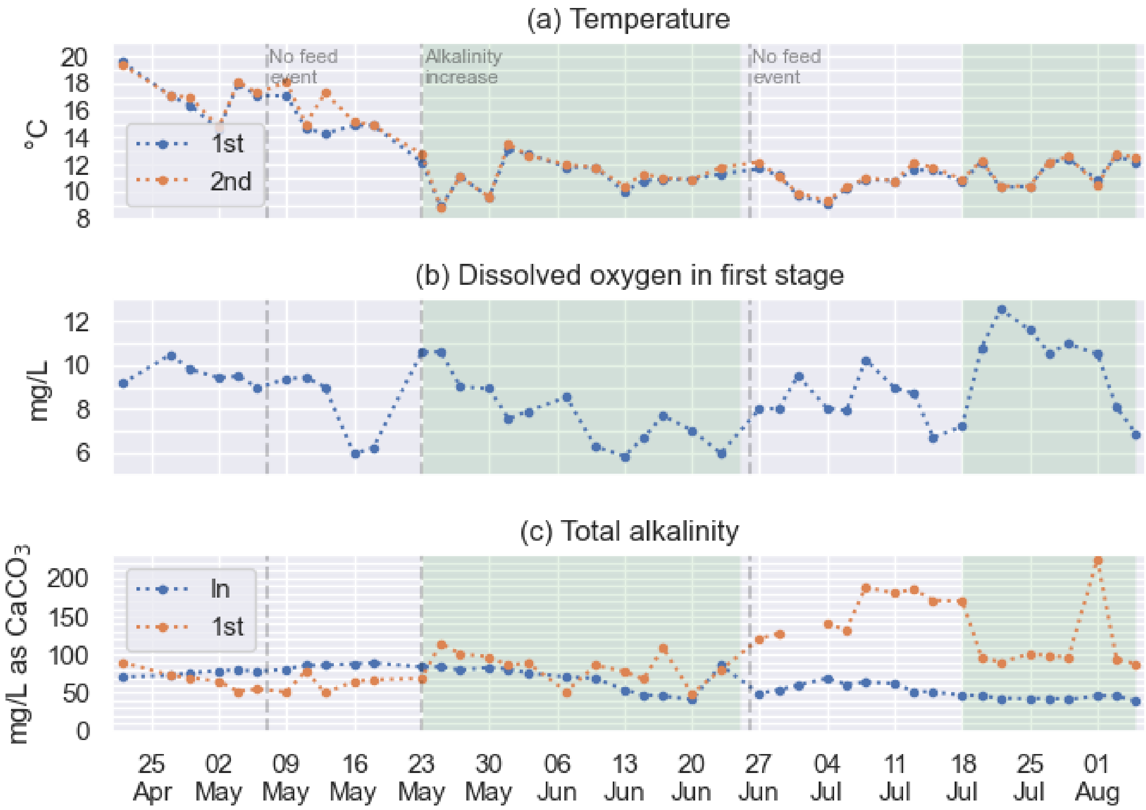


(a) 31 days (b) 62 days (c) 106 days

ENVIRONMENTAL CONDITIONS

Figure 6 shows a few important parameters during the trial. Most of the stable operation took place at lower temperatures between 10 and 13°C. The influent and stage 1 effluent alkalinity is also shown. Dissolved reactive phosphorus is not shown, but was monitored, and no phosphorus limitation was observed during the trial.

Figure 6: Environmental factors



RESULTS

CONCENTRATIONS AND LOADS

The TAN and NOx concentrations throughout the plant are shown in *Figure* 7. For TAN, the relevant concentration with regards to performance is after the first stage. There is TAN removal through bioassimilation in Stage 2, but it is not a controlled process and should not be relied on for total nitrogen removal performance. The increase in NO_x from the influent to the first stage is the TAN that is converted to NO_x. The TAN and NO_x loads and removal are shown in *Figure* 8.

After the start-up phase, the performance was impacted by process upsets, which were described above. Under normal operating conditions, the system performed reliably. These are the above described periods one and two, when both nitrification and denitrification perform.

In the first part of the trial, from start to 27 June 2022, the intention was to maximise the TAN and NO_x removal load of the system by running at a feed flow of 10.1 L/min to keep a higher substrate concentration in the reactor.

In the second part, the aim was to achieve TAN (after 1st stage) and NO_x effluent concentrations of below 1 mg N/L, and thus decreased the feed flow to 5.6 L/min. The very low effluent concentrations and high DO concentration in Stage 1 indicate that the system was underloaded in that final period. As a result, the flow was increased for the last two datapoints.

Figure 7: Ammoniacal nitrogen, nitrate & nitrite concentrations in the plant's influent, 1st stage and 2nd stage.

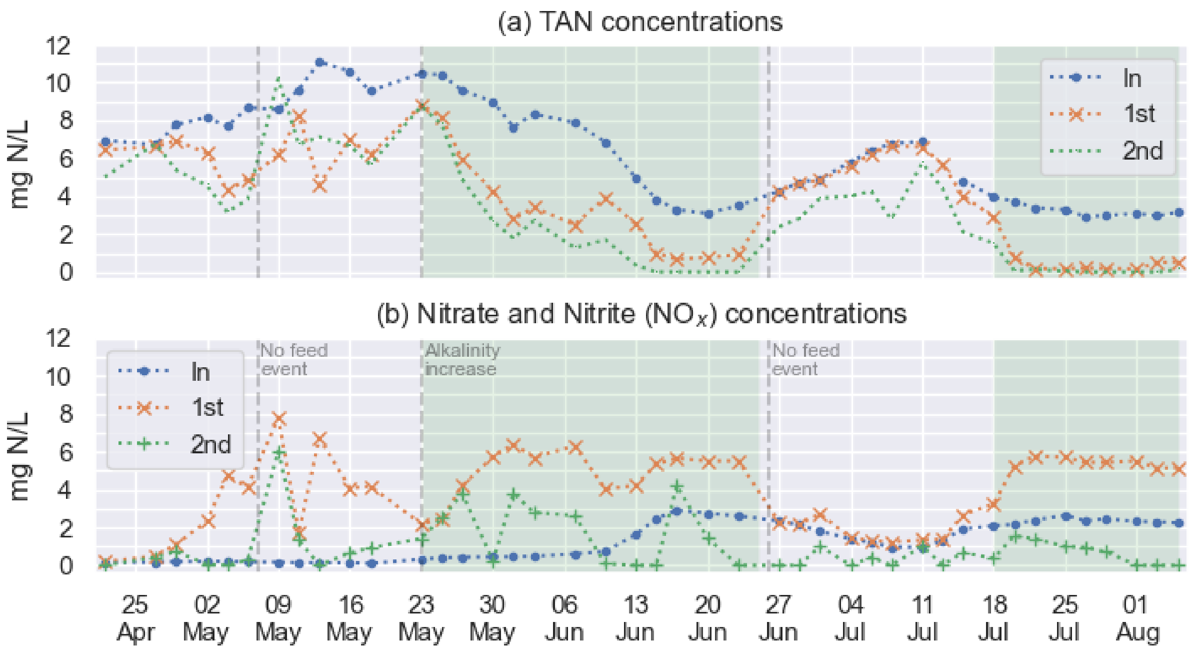
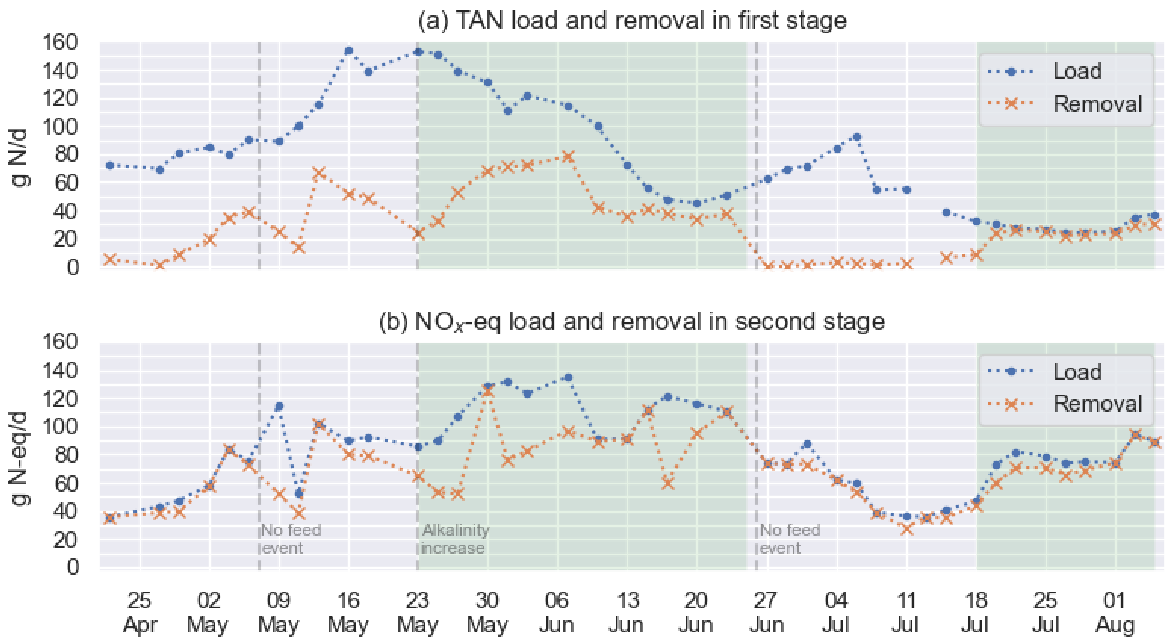


Figure 8: TAN and NO_x-N_{eq} load and removal

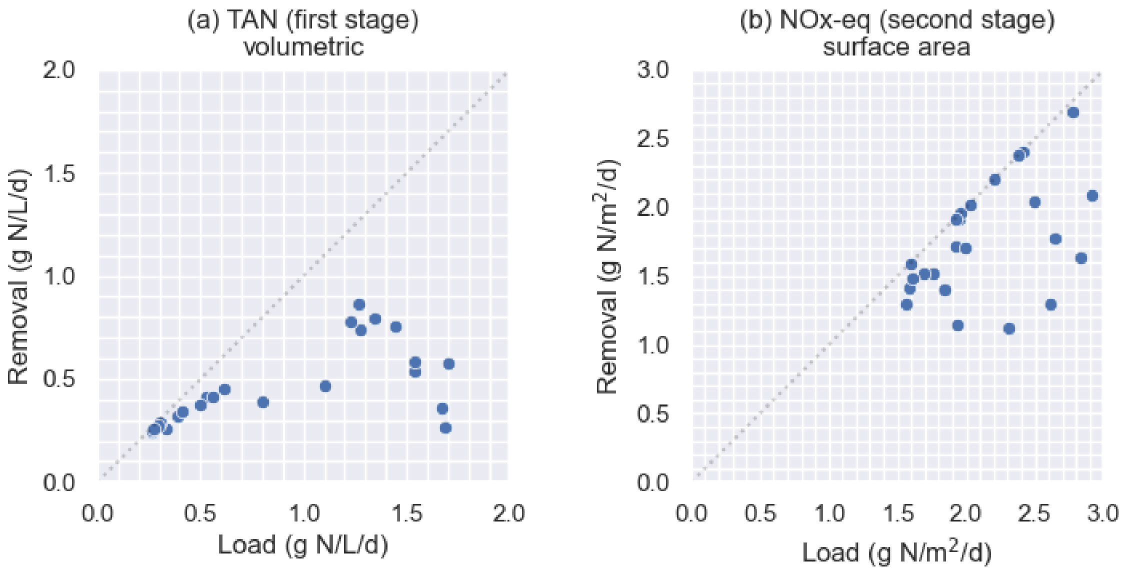


VOLUMETRIC REMOVAL RATES (VRR) AND SURFACE AREA REMOVAL RATES (SARR)

The surface area removal rate (SARR) is a critical design and performance parameter for biofilm systems including MBBR. As the NOx-Neq removal was known in Stage 2 along with a defined media surface area, the SARR for denitrification (in g N/m^2/d) could be calculated according to equation (1).

For the nitrification stage (first tank), the actual SARR could not be determined because of the unknown specific surface area of the new carrier media type. Instead, the removal rate per litre of carrier media (g N/L/d) was calculated. The removal rates are presented in *Figure* 9. Only the values where the pilot was operating stable are presented (the green shaded areas).

Figure 9*: Load vs removal for TAN (in first stage) and NO_x -N_{eq} (in second stage). Note: TAN is as volumetric (per litre carrier media), NO_x-N_{eq} is as surface area*



The results for TAN indicate that the pilot system was operated at its capacity under the environmental conditions. The results for NO_x-N_{eq} indicate that the denitrification stage seems to have further capacity. The average temperature in the two periods was between 10 and 13°C. An increase in temperature will also increase the removal rates.

A timeline of the actual VRR and SARR results are shown in *Figure 10*. These are comparable with calculated theoretical rates based on MBBR sizing guidelines. It was anticipated that Stage 1 would achieve a removal of approximately 0.6-0.7 g N/L/d without substrate limiting conditions, and Stage 2 would achieve 2.0-2.5 g N/m^2/d without substrate limiting conditions. It should be noted that substrate limiting conditions for post-denitrification start at effluent NO_x-N_{eq} concentrations as high as 10 mg/L with a significant decrease in removal rate starting at effluent NO_x-N_{eq} concentrations below 5 mg/L.

Using the measured TAN removal (g/d) and the theoretically expected nitrification SARR (g N/m^2/d) based on the measured environmental factors, the effective surface area of the Stage 1 media is estimated to be between 800 and 1000 m^2/m^3. Due to the small pore openings in the media, it is suggested that this calculated effective surface area would only apply for nitrification where the biofilm thickness is relatively thin. Use of this media with heterotrophic bacteria would likely result in lower effective surface area as the pores would likely become overwhelmed with biofilm.

Figure 10: Measured TAN VRR (g N/L/d) and NO_x-N, NO_x-N_{eq} SARR (g N/m²/d)

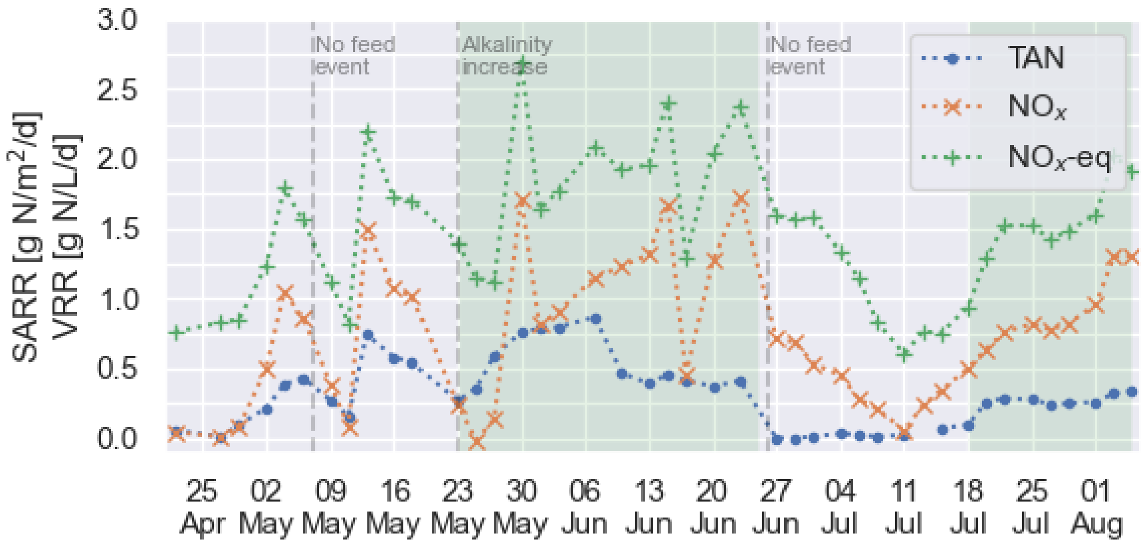


Table 4 presents average values for VRR, SARR, removal percentages and temperatures for the two periods where the plant operated reliably.

Table 4: Average values for the two operational periods where the plant performed. Period 1 includes data from 28 May to 26 June, period 2 from 21 July to 5 Aug 2022

Parameter	TAN VRR	NOx SARR	NOx-eq SARR	TAN removal	NOx removal	NOx-eq removal	Temp.
Units	g/L/d	g/m²/d	g/m²/d	%	%	%	°C
Period 1	0.57	1.23	2.02	64%	74%	82%	11.1
Period 2	0.28	0.96	1.64	91%	90%	94%	11.7

DISCUSSIONS

The results of the two periods (period one with focus on a high load, and period two with focus on low effluent concentration period) showed that the trial objectives could be achieved. The plant was able to remove TAN and nitrate concentrations to below 1 mg/L. The measured empirical VRR and SARR are comparable to expected removal rates, albeit slightly on the lower range.

In this trial the pilot plant was operated during winter conditions, with average water temperatures around 11°C. The low temperatures result in reduced activity and SARR.

The long laboratory sampling turn-around time was challenging at times. It meant that serious process upsets were only recognised one to two weeks after the measurements were taken. The setting of the alkalinity and acetic acid dose rates was based on samples in the past, and a necessary guess of how the environmental and plant parameters had changed since the last sample results.

For the next trial, the sampling will be performed in-house, which should result in a more efficient trial experience. It will enable for more dynamic response, and thus push the pilot plant closer towards its performance limits. This should potentially increase the measured VRR and SARR rates (note that higher temperatures will also increase those rates).

Biological phosphorus removal has not been demonstrated reliably at full scale with fixed film process including MBBR. If a treatment plant were also required to include phosphorus removal, chemical phosphorus removal can be implemented downstream of the MBBR with the coagulated effluent settling in a polishing pond or undergoing filtration through membranes, sand filter, disc filter, etc.

While not discussed in this paper, the effluent suspended solids were measured, with a mean value of around 55 mg/L. Any downstream TSS removal step should be combined with the above mentioned phosphorus removal requirements, such as a disc filter or membrane filtration.