MEMBRANE AERATED BIOREACTOR (MABR) PILOT TESTING

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ABSTRACT

Membrane Aerated Bio Reactors or MABR's are a new technology for the treatment of wastewater. The process is reported as being very energy efficient, having lower nitrous oxide emissions than alternative processes such as activated sludge. It is also ideal for process intensification where additional total nitrogen removal or nitrification (conversion of ammonia into nitrate and nitrite) is required.

Most MABR installations and pilot scale plants around the world have been operated in hybrid mode where the MABR membranes are used within an activated sludge reactor (typically the anoxic zone). In this application the MABR augments the activated sludge process by providing an aerated carrier onto which a nitrifying and denitrifying biofilm can develop. This means that nitrogen removal via nitrification and denitrification can occur in the same reactor and in the same space.

This pilot study looked at the application of MABR in a biofilm only mode. In this mode the process could be used to either nitrify or denitrify without the need for mixed liquor in the liquid phase. This application of MABR is potentially very well suited to process upgrades in New Zealand where oxidation pond systems are required to meet tighter nitrogen consents year-round, often resulting in these being replaced with activated sludge plants such as SBR or MBR, that are energy intensive. In addition, MABR processes may have lower N2O emissions per unit of nitrogen treated and are therefore of particular interest to Watercare in our goals to meet net zero emissions by 2050.

This paper presents the results of piloting undertaken by Watercare Services Limited with a SUEZ ZeeLung MABR in biofilm only operation mode. The goal of the trail being to understand the efficacy of the process in terms of nitrogen removal from raw or primary wastewater without mixed liquor, to quantify N2O emissions and to better understand how a full-scale system could be configured and commissioned.

KEYWORDS

MABR, nitrification, denitrification, Nitrous Oxide

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INTRODUCTION

The membrane aerated biofilm reactor (MABR) process is an innovative technology that offers for a wide range of applications. The MABR process employs a gas permeable media to deliver oxygen to a biofilm that is attached to the surface of the media. Oxygen is delivered to the biofilm by molecular diffusion, without the use of bubbles, resulting in energy efficient treatment independent of tank depth. This bubble-less oxygen transfer produces a unique environment within the biofilm where oxygen enters from one side and substrate (ammonia, organics) enter from the other side. This creates a range of process opportunities, including performing nitrification in reactors that are not otherwise aerated and developing different strata of microbes through the depth of the biofilm.

Figure 1 shows the structure of an MABR membrane and biofilm versus that of a conventional carrier process such as MBBR

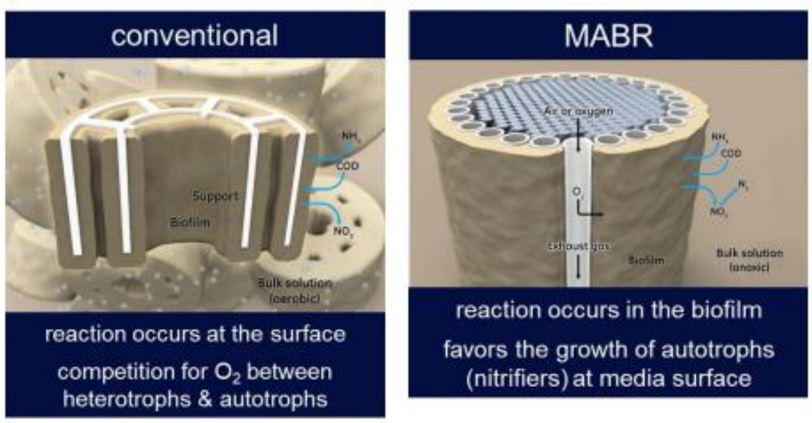


Figure 1: MABR compared to Conventional Biofilm

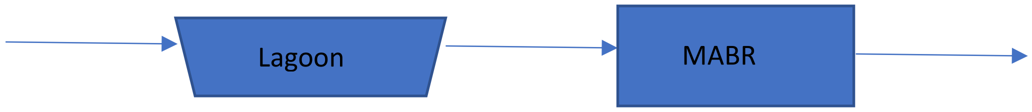
MABR TECHNOLOGY

MABR technology can be used in a range of applications. The most common is the upgrade of conventional activated sludge (CAS) plants for nutrient removal and capacity expansion in existing tank volumes (Kunetz et al., 2016). In this application, MABR intensifies treatment capacity and improves performance by increasing the biomass inventory while also significantly reducing the energy required for aeration. For this hybrid configuration, MABR media is installed into an activated sludge reactor, typically in the anoxic zone. A biofilm grows on the media surface and increases the total inventory in the system at the same suspended growth mixed liquor concentration.

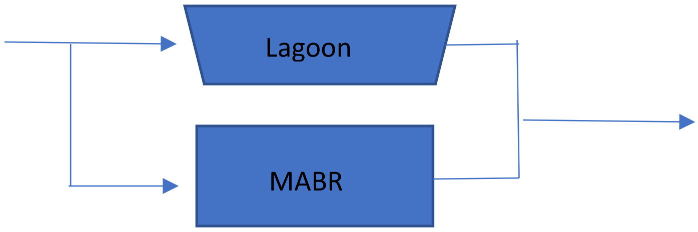
In a Biofilm configuration, membranes are located in a standalone reactor without activated sludge. This means that the process can be retrofitted as a side stream to an existing process to boost nitrification and denitrification.

Depending on the treatment goals of the process, a biofilm only MABR can also be added as a tertiary system to boost nitrification performance. In a tertiary system, denitrification is possible with the additional of an external carbon source such as acetic acid. In a parallel configuration, the MABR can be used to reduce load on a lagoon system, whist providing simultaneous nitrification denitrification without the need for a multistage process.

These two concepts are shown in Figure 2



Series or Tertiary Configuration



Parallel Configuration

*Figure 2:	Conceptual Configurations for BioFilm MABR*

WHY ARE WE INTERESTED IN THIS TECHNOLOGY?

Watercare are interested in MABR as it meets many of our 40/20/20 goals including:

- Small footprint – the process has the potential to significantly reduce the size of nitrogen removal systems and depending on where in the process train an MABR is installed, it can provide nutrient removal without multiple stages of treatment, thus lowering imbedded or capital carbon
- Shallow reactors – MABR has the potential to provide very high levels of aeration efficiency in a shallow tank, consuming less aeration energy than activated sludge. This means that for sites with poor ground conditions,

less ground improvements are needed saving time and cost in construction

- Modular – MABR can be installed in reactors that are built of materials such as stainless steel that are fabricated off site meaning less time is required onsite to build large concrete structures.
- Potentially lower nitrous oxide emissions than conventional processes. This will allow us to meet our emissions targets by 2030 and beyond
- Operational cost savings due to aeration being 3-4 times more efficient than activated sludge, SAF or MBBR systems.

HOW DOES IT WORK?

In biofilm only mode the membranes are submerged in a tank or reactor – in this pilot we used three Zee Lung modules placed within a 3.2m deep tank.

Figure 3 shows how a typical Zee Lung cassette is configured.

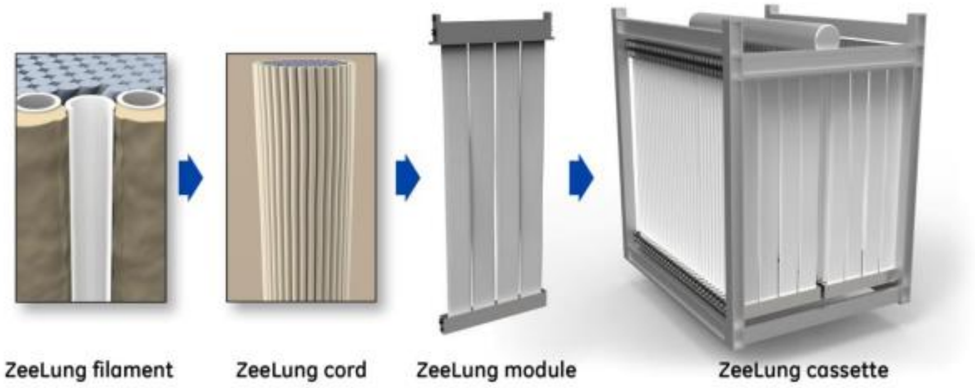


Figure 3: ZeeLung MABR Product

The MABR works by growing a biofilm directly onto the membrane surface. Unlike other fixed film technologies such as MBBR or trickling filters, the oxygen for the biofilm is provided from one side whereas the substrate (carbonaceous compounds) or ammonia diffuse from the other. This is shown in figure 4

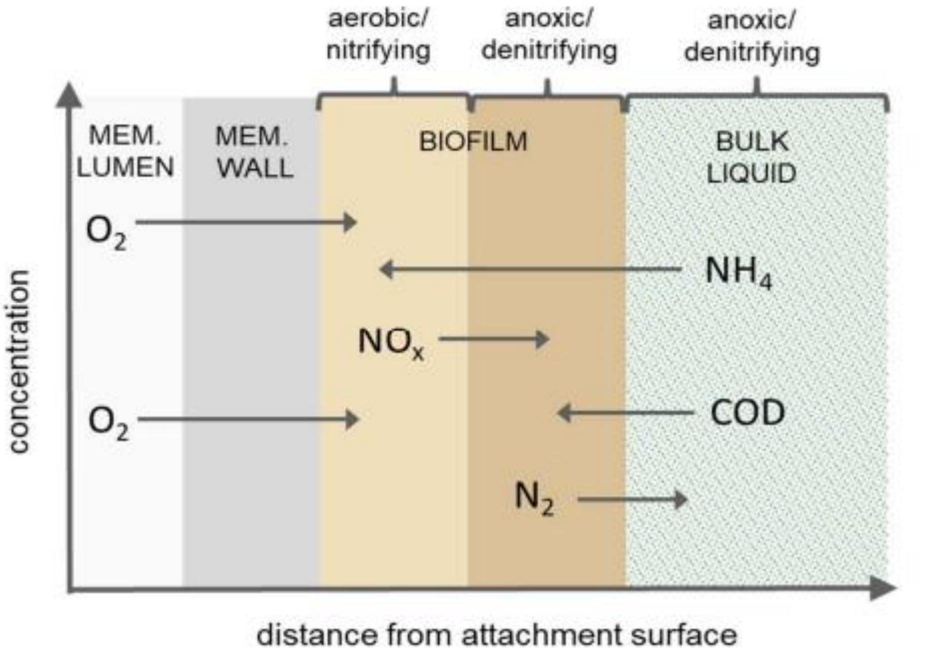


Figure 4: Counter Diffusional BioFilm

A counter diffusional biofilm has some unique characteristics:

- Oxygen is applied directly to the biofilm via molecular diffusion over a large surface area, making the system very efficient at transferring oxygen
- By products of the biological reactions inside the biofilm can diffuse either into the bulk liquid phase or into the exhaust gas stream depending on mass transfer conditions in the reactor
- As substrates diffuse into the biofilm and oxygen diffuses out, several layers of biological activity can be established. Organisms such as nitrifiers that need oxygen, grow close to the membrane lumen. Heterotrophic organisms (that consume BOD in the wastewater) and can survive in lower oxygen environments grow in second layer. These organisms can also convert nitrate to nitrogen gas via denitrification and therefore nitrate that is produced by nitrifiers can be denitrified as the nitrate diffuses out toward the bulk liquid phase. A third layer can also be formed at the outside of the biofilm, containing sulphur reducing bacteria or other anaerobic organisms. There is the potential to use the sulphur cycle to further enhance denitrification, although this was not studied in this pilot.

In biofilm mode there is no mixed liquor recycle, no dissolved oxygen measurement and no mechanical mixing of the tank contents.

WHAT MABR IS NOT

MABR is not a filter as the membranes do not do any physical filtering. The membrane lumen is essentially a support structure for a biofilm to grow, providing a similar function to media in a trickling filter or MBBR. The media is similar in many ways to integrated fixed film activated sludge (IFAS), however it performs two functions: namely biofilm support and diffusion of oxygen directly into the biofilm.

MABR is not an aeration diffuser. While the membrane lumen provides oxygen, it does this via molecular diffusion of the oxygen through the wall of the membrane "tube" directly into the biofilm. This system of providing oxygen, does so without any bubbles and this means that some of the limitations of dissolving air into water via small bubbles from an aerator are overcome.

PILOT PLANT SET UP

The pilot was conducted at the Mangere WWTP innovation centre – this location was chosen due to access; availability of services and we were able to integrate the pilot with other systems at the innovation centre such as N2O monitoring.

Photo 1 shows a membrane module installed in its support from before installation and Photo 2 shows the pilot skid awaiting installation at the innovation centre.

Photo 1: Membrane Modules and Support Frame

The membrane modules are arranged in a frame with air connections at the top and bottom. Process air is connected to the base of the support frame and is drawn off from the top of the modules. Process air is applied at a constant rate of 4-5L/min or approximately 8m^3/hr per full scale cassette.

Wastewater is pumped from the settled sewage channel at Mangere into an 8m^3 balance tank via a self-priming dry mounted pump. From the balance tank a pump fitted with variable speed drive delivers between 4 and 10m^3/d to the pilot tank. Process air is supplied to the pilot via an air compressor mounted on the pilot skid and/or from the site compressed air. This process air is filtered, and pressure is reduced from 5-6bar to between 0.6 and 0.7 bar. Exhaust air oxygen content, CO_2 and nitrous oxide content are measured via MAMOS gas analysers (see photo 3)

Photo 2: MABR Before Installation

Effluent from the MABR reactor flows over a weir by gravity and is discharged to drain.

In addition to the process air, the pilot has mixing air and scour air. These are used to mix the contents of the reactor to minimise any solids settling and to ensure that substrate is "refreshed" at the membrane liquid interface. This minimises the risk of diffusion limiting treatment performance. Scour air is applied to the membranes via a LEAP aerator (the same as on SUEZ MABR systems). This provides a stream of course bubbles that scour biomass off the membrane surface to manage its thickness. Both systems on this pilot are run via timers and control valves that are operator adjustable.

Photo 3: Off Gas Analyser

PILOT PLANT GOALS

The goals of the MABR pilot carried out at the Mangere Wastewater Innovation Center were:

- Prove that the biofilm concept can nitrify and will work as a concept
- To determine what nitrification rates could be achieved in a biofilm only process configuration
- To determine if nitrification and denitrification occur simultaneously in the process and to what extent
- Determine nitrous oxide emission rates
- Develop an understanding of the way the process operates, what maintenance is required and what operator input is required.

PILOT DURATION

The polit at Mangere Innovation Center was run in biofilm only mode for a period of 16 months to the end of August 2022. During this time the plant was run in several modes and the operating setpoints for mixing, membrane scour and loading rates (both COD and ammonia) were determined. The results below are a summary of the optimized settings. A description of the remainder of the trail will be presented elsewhere, including how the settings were optimized and the analysis undertaken to determine these.

RESULTS AND DISCUSSION

LOADING RATES AND REMOVAL EFFICENCY

The sizing of an MABR is based upon a media loading rate i.e g or kg of ammonia per square meter of surface area per unit time (days). A typical design loading rate for a nitrifying system in hybrid mode is approximately 2g/m2.d. Removal efficacy is measured by sampling of the inlet and outlet ammonia concentrations and is typically referenced to a removal rate expressed in gN/m2.d. It was assumed that nitrification rates would be the same or similar in a biofilm only process, however the trial was used to determine if this rate were achievable in this configuration.

NOTES ON LOADING RATES

While MABR is a potentially effective system for nitrification, there are a few important points that make design and operation of an MABR different from conventional processes.

An MABR, while capable of achieving very low effluent ammonia concentrations (<2mgN/L), reduces in efficiency at low bulk ammonia. This is due to diffusional limitations - as the concentration of ammonia in the bulk phase reduces the driving force for diffusion also reduces. This means that at low ammonia concentrations the rate of removal drops very significantly. At concentrations below 5mgN/L the rate can be as low as 20 -25% of the maximum and slows significantly at concentrations under about 10mgN/L. If very low ammonia concentrations are needed, the membrane surface area needed increases, and therefore the capital cost.

For this reason, the optimum configuration of a biofilm MABR is plug flow such that only the last reactor or cassette in series is exposed to low ammonia concentrations. Given that biofilm mode has no recycle it should provide for high ammonia loadings on the first tank or cassette in series.

The system is not designed on a hydraulic loading rate and therefore there is no biological limit on the peak flow that can be passed through an MABR system. During design factors such as weir length and tank free board are likely to represent the major constrains for hydraulics rather than the activity of the biofilm.

Oxygen limitation in MABR can occur, although we have not observed this in the pilot trail. At exhaust gas oxygen concentration under about 8% its likely that that maximum rate wont be achieved due to limitations in the partial pressure of oxygen in the process

NITROGEN LOADING RATES

Ammonia loading rates during this period of the trail averaged 2.27g/m2.d, with the influent ammonia concentration ranging between 18mgN/L and 50mgN/L. These variations are primarily due to the load that the Mangere Plant was receiving and the flow that has been very heavily influenced by rainfall.

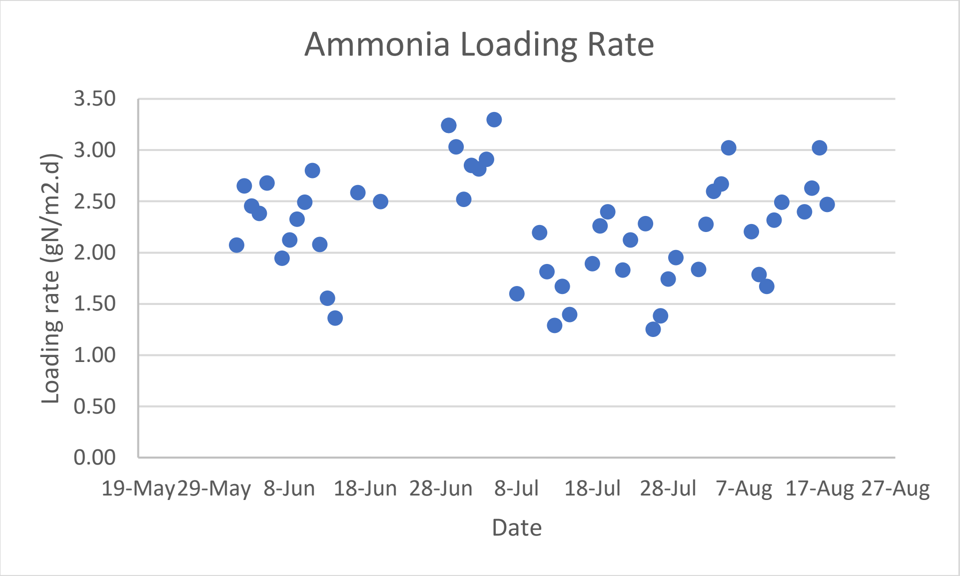


Figure 5: Ammonia Loading Rate

Figure 6 summaries the nitrification rate of the MABR measured between May and August 2022

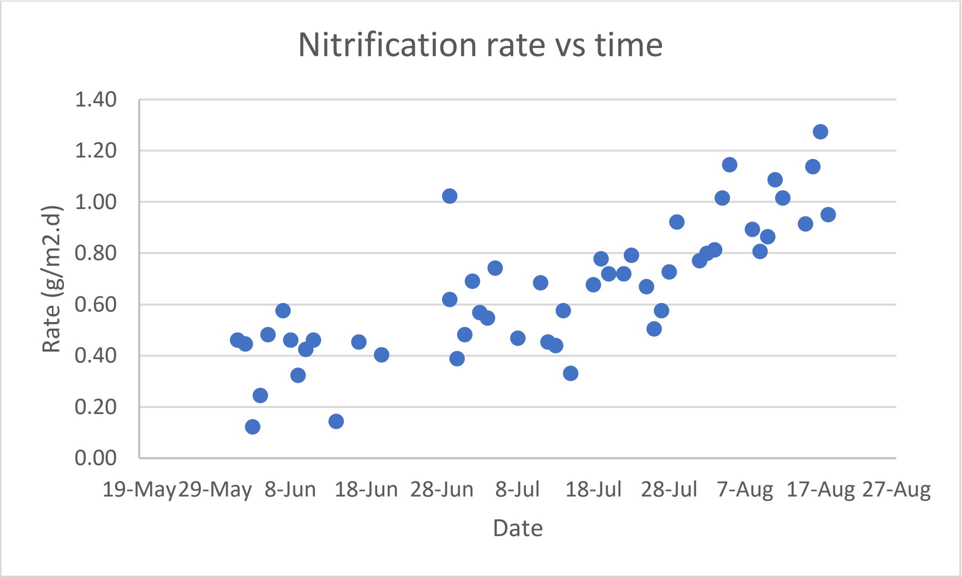


Figure 6: Nitrification Rate

The nitrification rate increased during this period of the trail from approximately 0.4gN/m2. to 1.3g/m2.d. This is due to the ongoing optimization of the biofilm thickness and diffusivity. The results show that the process can nitrify successfully in this mode of operation, when the scour settings were optimized. Based on these results and the settings used, it appears that a nitrification rate of 1.0-1.3g/m2.d can be sustained.

While not presented in this paper the pilot was also run-in conditions where final effluent was spiked with ammonia and alkalinity. These results showed that the nitrification rate could be maintained closer to 2gN/m2.d. This suggests that arranging the MABR in a series or plug flow configuration, that the first tank would have a nitrification rate in the region of 1-1.3g/m2.d and the second could be expected to have a rate closer to 2g/m2.d resulting in an overall rate of between 1.5 and 1.75g/m2.d.

The difference between rates in different tanks is hypothesized to be due to the thickness of the biofilm

DENITRIFICATION

Figure 7 shows the effluent nitrate from the MABR pilot over the period 29 May to 23 August 2002. During this period no external carbon source was added. As shown in the figure the effluent nitrate is consistently low across a range of operating conditions. The average denitrification performance of the system (based on the mass of ammonia nitrified) is 91% over this period. This result illustrates that the MABR in this mode is capable of almost complete denitrification given a suitable COD to ammonia ratio.

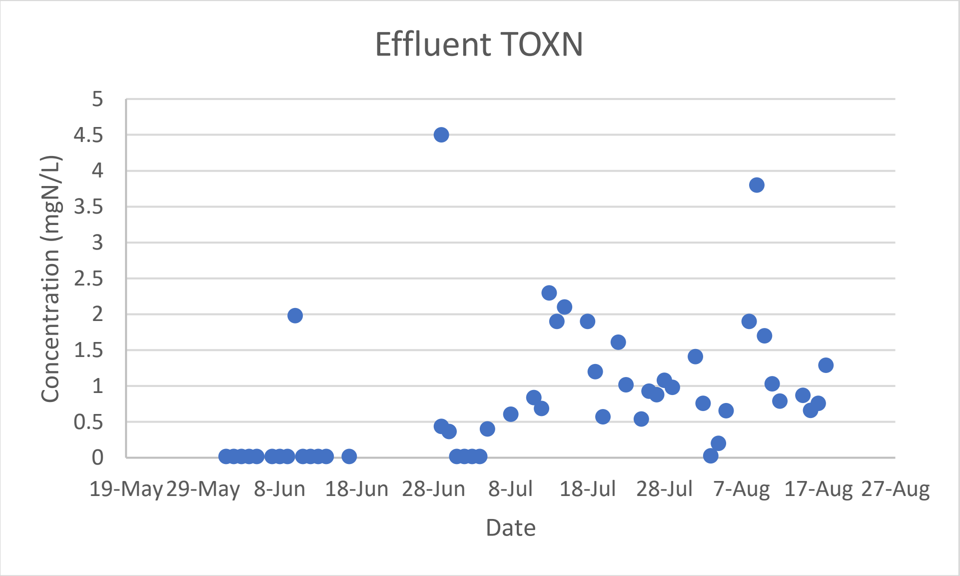


Figure 7: Effluent Nitrate

OXYGEN TRANSFER

Oxygen Transfer in MABR is considerably higher than in fine bubble system. This reduces the power required for process aeration and makes the system a lot more energy efficient than conventional aeration systems.

Aeration efficiency is measured only under field conditions – i.e as OTR or OTE. Unlike fine bubble aeration systems there is no or very limited mass transfer in clean water. Equivalent measures of aeration efficiency such as Standard Oxygen Transfer Rate (SOTR) or Standard Oxygen Transfer Efficiency (SOTE%) are not relevant to an MABR. In addition, given that the transfer of oxygen is very high, account needs to be taken of the volume difference of the input and exhaust process air due to the "loss" of oxygen from the input air.

For an MABR the Oxygen Transfer rate is calculated as follows:

$$V_{\%} = (100 - 20.95)/(100 - Off\ Gas\ O2)$$

$$OTE\% = (20.95 - Offgas\ O2)/20.95$$

$$OTR = (Q_{air}\ * (1 - V_{\%})/(Molar\ Mass\ Air)/(molar\ mass\ Oxygen))/SA\ membrane$$

Figure 8 shows the measured OTE% from the MABR from May to August 2022. Average efficiency is 28%, and as the system nitries at a faster rate (right hand side of figure 8) the OTE also increases. These results confirm that the process has a very high transfer rate – for comparison in a 3 m deep tank OTE% of a fine bubble diffuser is approximately 7-9% (15-20% SOTE%)

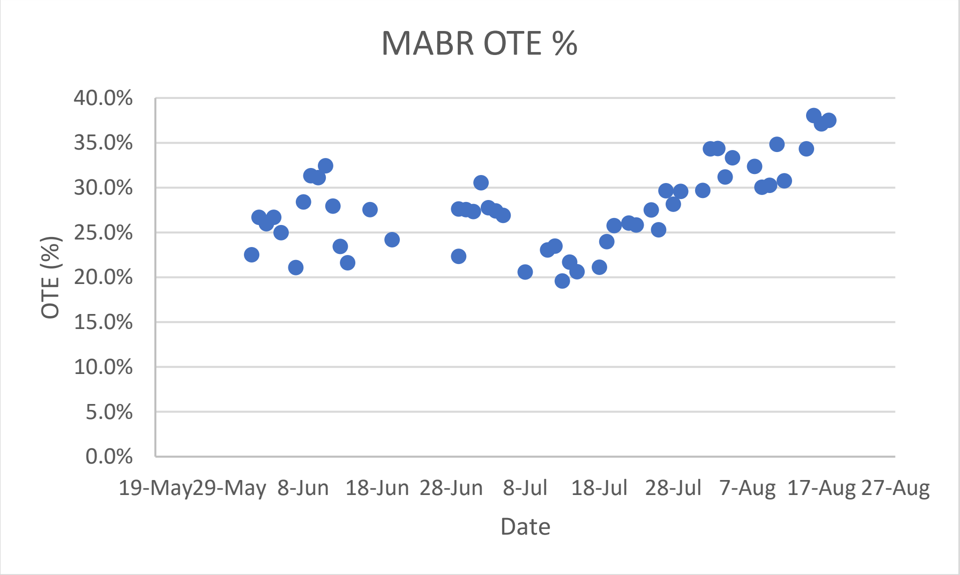


Figure 8: MABR Oxygen Transfer Efficiency (%)

CARBON EMISSIONS

Scope one carbon emissions consisting of nitrous oxide and methane are key components of Watercares carbon footprint and represent a significant challenge in meeting our future goals of a 50% reduction in emissions by 2030 and net zero by 2050. MABR processes have been reported (Houwling et al, 2021) as having lower process emissions than activated sludge and potentially significantly lower than emission factors specified by the IPCC.

There is no published data available on N2O emissions from a biofilm MABR. This pilot therefore included quantification of N2O in the exhaust gas and calculation of a CO2eq emissions factor. This was undertaken by installing a dedicated N2O analyzer on the process exhaust gas stream. Given that this is the only significant (and constant) supply of air to the process it is the most likely place where N2O, if present, could be measured.

It is noted that there is mixing, and scour air applied to the process and this may give rise to N2O stripping from the liquid phase and discharge to atmosphere.

Investigations into this are continuing and at the time of writing this paper, indications are that this source of N2O is very low compared to the process exhaust air. These results will be presented in a future paper.

Figure 9 below shows the N2O concentration (in ppmV) based on daily recordings from the analyzer.

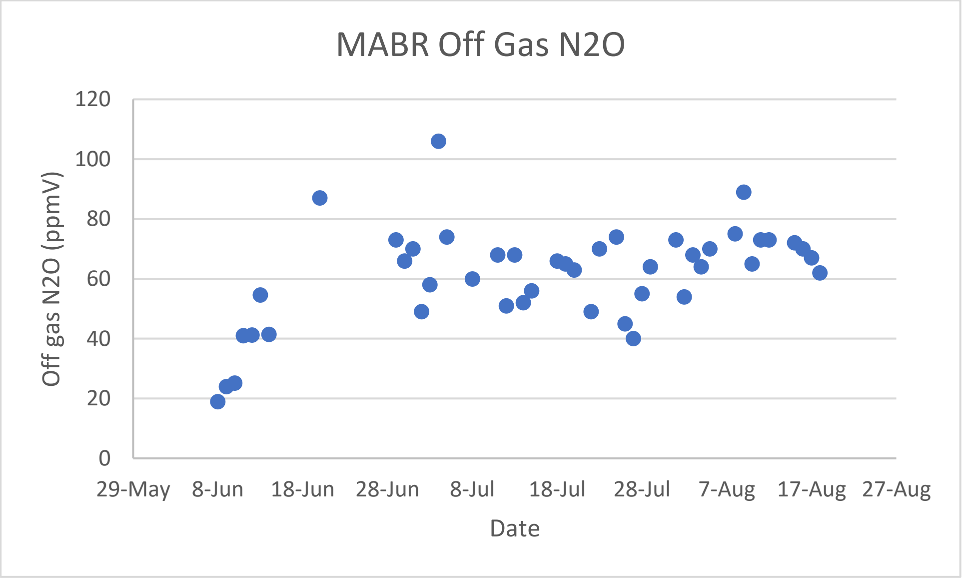


Figure 9: Off Gas N2)

Figure 10 shows a snap shot of continuous N2O data from the analyzer.

Figure 10: example of Continuous offgas N2O Measurement

EMISSIONS FACTOR

The raw N2O figures have been converted into an emissions factor (gN2O-N/gNH4-N) using the following methodology:

$$Mass\ N2O = \frac{X\ part\ gas}{1\ million\ parts\ air} * \frac{44gN2O}{mol} * Air\ flow\left(\frac{Nm3}{d}\right) * 22.711\left(\frac{Lgas}{mol}\right) * \frac{molmass\ N}{molmass\ N2O}$$

This converted data is shown in figure 11

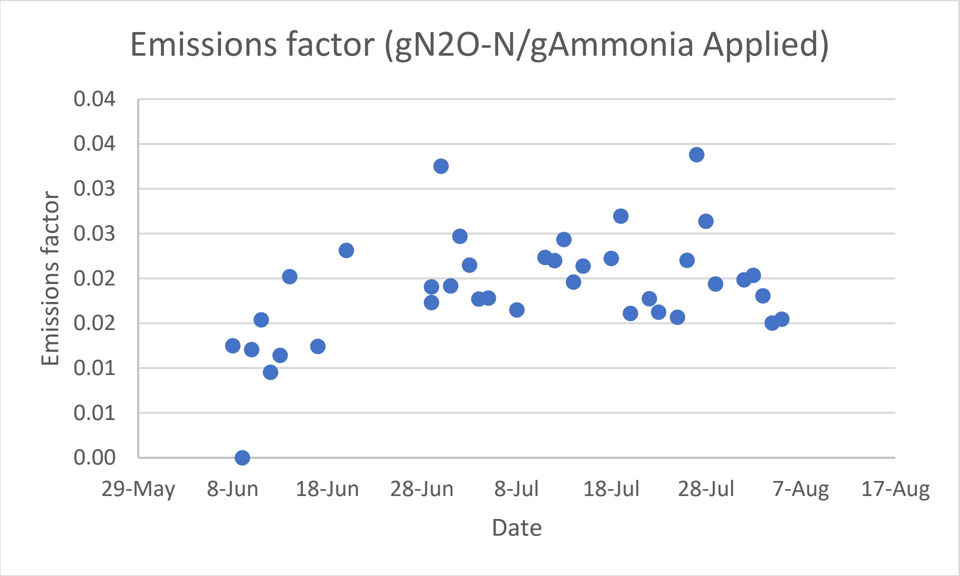


Figure 11: Measured Emissions Factor

The average emissions factor from the MABR was 0.02gN/gN (or 2%). This is a very similar value to that reported for nitrifying and denitrifying activated sludge processes and appears higher than expected (Conley, 2021). However, it is difficult to compare this to a factor developed for other plants treating different wastewater under different conditions. Hence the next phase of work we are undertaking is to measure the N2O emission rate from a pilot activated sludge process treating the same flow from the same source to provide a baseline that these results can be compared to. This work is underway and will be completed by the end of 2022.

This pilot has however provided the first direct measurement of N2O for a biofilm only MABR and gives us some specific, measured data on which to based future investment decisions.

CONCLUSIONS

The primary goal of the pilot trails was to prove that the biofilm only MABR concept was feasible, was able to nitrify and to achieve reasonable nitrification rates in a real application.

The trial has shown that the concept is feasible and can be implemented in a number of different scenarios. We have also used the trail as a means to further our understanding of how to quantify nitrous oxide emissions. As a result of this work Watercare is installing two MABR processes, the first of which should be operational in early 2023.

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