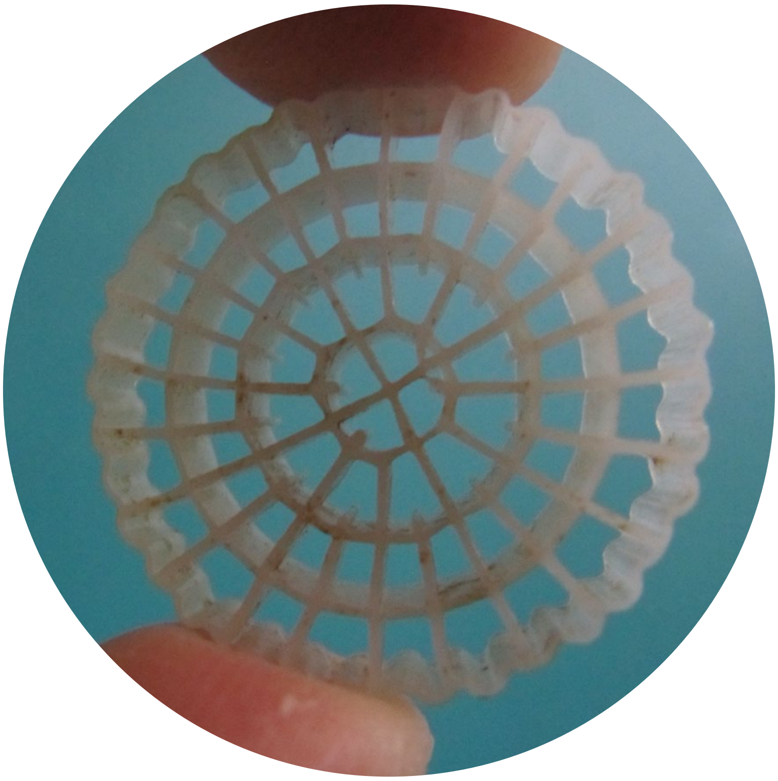
Denitrifying MBBR Guide



1 Choice of MBBR technology

A range of purification techniques can be considered for removing nitrate from water, such as ion exchange, reverse osmosis, biological denitrification, electro-dialysis and distillation. Biological treatment is viewed as highly attractive, because it is cost-effective and environmentally friendly[i], while the use of the other purification processes is limited owing to the high capital and energy costs[ii].

Conventional biological denitrification via a system with activated sludge in suspension is not recommended for treating drainage water from field drainage. This results from the typical characteristics of drainage water as we know it in Flanders; high nitrate concentration, cold water temperature and seasonal fluctuations in water drainage (depending on precipitation, composition of the soil). Under these circumstances, a high removal efficiency cannot be expected via activated sludge systems. Because the purification facilities in the field need to be placed close to the drainage tubes, it is important for a compact solution to be developed, such that as little field surface area as possible is lost. Through the application of a biofilm process, whereby the active biomass grows on specially developed carriers, we can ensure a smaller reactor footprint compared to the classical activated sludge (AS) process. The carrier medium that serves as an adhesive surface for the micro-organisms ensures that a higher (active) biomass concentration can be reached. On the other hand, the carriers can also cause excessive growth of biomass, which can cause clogging in the reactor. The MBBR technology (Moving Bed Biofilm Reactor), which was developed in the late eighties and early nineties in Norway, is a biofilm process whereby the biomass grows on a plastic carrier that are (periodically) kept in motion using mechanical mixers and/or aerators in the reactor room. This means the MBBR is not hindered by clogging and subsequent motion and collision of the carriers. As opposed to the AS technology, the MBBR does not require a settling tank for the separation of solids from the purified water, and the system's performance is thus independent from the sedimentation yield. Moreover, it is a cost-effective and highly efficient purification that requires little maintenance[iii]. An MBBR can be used under very heavy load and the process is not sensitive to variations in load[iv].

2 Carbon source dosage

Because there can be high concentrations of nitrate present in the drainage water, dosage from an external carbon source is necessary. The results of these tests demonstrate that, when there is insufficient dosage from a carbon source, NO_3^- is converted into NO_2^- instead of being fully reduced to N_2 nitrogen gas. Because the NO_2^- is highly toxic to fish, it is important to reduce the NO_3^- fully[v].

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[i] Dahab, M. F. and Y. E. Lee. *Nitrate removal from water supplies using biological denitrification*, J.WPCF, n. 60, 1988, pp. 1670-1674.

[ii] K.A. Karanasios, I.A. Vasiliadoua, S. Pavloub and D.V. Vayenas. *Hydrogenotrophic denitrification of potable water: A review*, Journal of Hazardous Materials, n. 180, 2010, pp. 20–37.

[iii] James P. McQuarrie and Joshua P. Boltz. *Moving Bed Biofilm Reactor Technology: Process Applications, Design, and Performance*, Water Environment Research; Jun 2011; n. 83 (6), p. 560-575.

[iv] Wisam Sabeeh Al-Rekabi. *Mechanisms of Nutrient Removal in Moving Bed Biofilm Reactors*, International Journal of Scientific & Engineering Research, January-2015, Volume 6, Issue 1, ISSN 2229-5518.

[v] Bjorn Rusten, Bjørnar Eikebrokk, Yngve Ulgenes &Eivind Lygren. *Design and operations of the Kaldnes moving bed biofilm reactors*, Aquacultural Engineering 34, 2006, pp. 322-331.

There are various types of carbon sources to be found on the market. In the first instance, the carbon must be present in solution and must be highly biodegradable. A wide range of carbon sources can be used. The most common are methanol, ethanol, acetate, acetic acid, glycerol and molasses. The choice of the most suitable carbon source is dependent upon the assessment of the safety, cost, ease of use, kinetics (the speed of the denitrification) and the effects at low water temperatures. Carbon sources from raw materials based on fossil fuels, such as methanol, ethanol and acetic acid, are subject to considerable fluctuations in price. Conversely, carbon sources of agricultural origin such as molasses, glycerol, corn syrup and saccharose have a predictable and less volatile pricing profile[vi]. Another aspect to be considered in choosing the most suitable carbon source is the start-up time, which is to say the time that micro-organisms need to grow and thus to be able to process high concentrations of NO_3^-. Methanol, for example, needs a long startup time, because only a few bacteria can break it down[v], while carbon sources such as glycerol and acetic acid can be metabolised by the general heterotrophic bacteria populations found in the wastewater treatment process[vi]. The chemical reactions for the denitrification of 3 different carbon sources are shown below:

Methanol:

$$5\mathrm{CH_3OH} + 6\ \mathrm{NO_3^-} \rightarrow 3\mathrm{N_2} + 5\mathrm{CO_2} + 7\mathrm{H_2O} + 6\ \mathrm{OH^-} \tag{1}$$

Acetic acid:

$$5\mathrm{CH_3COOH} + 8\ \mathrm{NO_3^-} \rightarrow 4\mathrm{N_2} + 10\mathrm{CO_2} + 6\mathrm{H_2O} + 8\ \mathrm{OH^-} \tag{2}$$

Glycerol:

$$5\mathrm{C_3H_8O_3} + 14\ \mathrm{NO_3^-} \rightarrow 7\mathrm{N_2} + 15\ \mathrm{CO_2} + 13\ \mathrm{H_2O} + 14\ \mathrm{OH^-} \tag{3}$$

It is important to note that the following reaction products are formed: N_2, CO_2 and H_2O, as well as OH^-. For every mol of OH^- produced, 1 mol of NO_3^- is removed. As a result, the denitrification produces alkalinity, which is to say that the pH of the water will increase as a consequence of removing the nitrate[vii]. Different carbon sources were tested out at lab-scale: molasses, Bio-aid, Carbo ST and Carbo BWB-60. Molasses is a viscous by-product of the sugar refinery industry; Bio-Aid is based on ethylene glyco butyl ether, naphthalene and vinyl acetate; Carbo ST mainly consists of glycerol[viii]; and Carbo BWB-60 consists of methanol (<2.5%) and glycerol[ix]. Carbo ST (€0.865/kg with a density of 1.25kg/L and a COD concentration of 1.5kg COD/L) and Carbo BWB-60 (€0.973/kg with a density of 1.20kg/L and a COD concentration of 1.0kg COD/L) can be ordered from this Dutch supplier: Melspring (https://afvalwaterbehandeling.watermelspring.nl/Koolstofbronnen).

COD or Chemical Oxygen Demand is a measurement of the quantity of organic material present in the solution. COD is expressed in mg O_2/L; this is a measurement of the oxygen consumption needed to oxidise all the organic components in the solution into CO_2 and water.

[vi] United States Environmental Protection Agency. *Wastewater Treatment Fact Sheet: External Carbon Sources for Nitrogen Removal*, August 2013.

[vii] Metcalf & Eddy. Wastewater Engineering, Treatment and Resource Recovery, 5th Edition, Vol 1, Mc. Graw-Hill, International Edition, ch. 7.

[viii] *Safety data sheet*, 1907/2006/EC, Art. 31, version num. 1, 18 Feb. 2014.

[ix] *Safety data sheet*, 1907/2006/EC, Art. 31, version num. 1, 15 Nov. 2013.

Please note that carbon source prices are heavily subject to supply and demand. The prices listed can therefore only be used to carry out indicative cost calculations. The quantity of biodegradable soluble carbon source needed for denitrification depends on the quantity of nitrate to be removed, the type of carbon source used and operational circumstances. The quantity of organic substrate to be added can be expressed in g COD per g of NO_3^--N to be removed. This is also known as the COD/N ratio or consumption ratio. Purely based on the redox reaction (reduction of nitrate to nitrogen gas, and oxidation of the carbon source), it is possible to calculate that 2.86g of COD/g NO_3-N is necessary. To provide enough carbon for the growth of biomass, 5 to even 8g of COD/g NO_3-N is dosed in practice to guarantee sufficient denitrification. In Figure 1 from Rusten et al., 1995[x], the effect of the COD/N ratio is clearly visible upon the MBBR's removal yield. A minimum dosage ratio of 4g COD/g NO_3-N to guarantee a high nitrate removal yield can be derived from this figure.

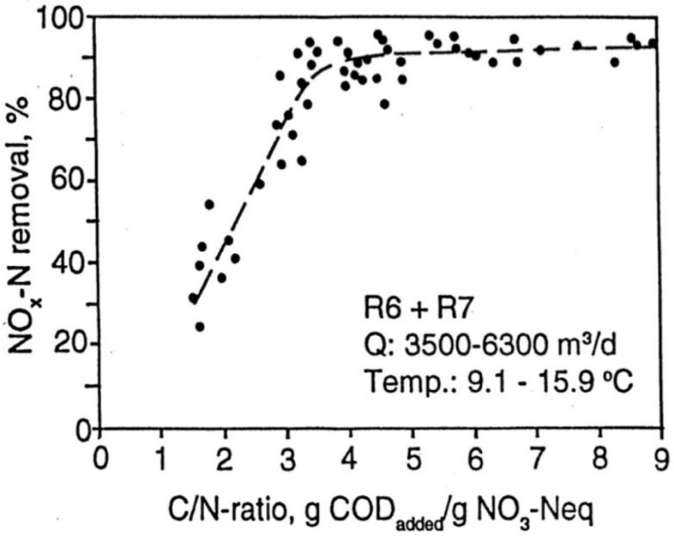

Figure 1: Relationship between the nitrate removal yield and the COD/N ratio employed (Rusten et al., 1995[x]).

A range of regulation scenarios are possible to achieve the right COD/NO_3-N dosage ratio at an MBBR facility. In the first place, for example, one could choose to measure the rate and nitrate concentration of the drainage water online and implement the dosage of the carbon source based on these parameters. Because this scenario involves a very high investment cost (>€25,000), this regulation strategic will not be practically feasible for the treatment of drainage water in economic terms. For small-scale MBBR facilities, it is therefore preferable to seek an economically feasible alternative that can still guarantee the dosage ratio. The most robust method of regulating the dosage of the carbon source is based on the MBBR's processing rate. This regulation strategy does presuppose that the influent concentration of NO_3-N to be worked with is fixed and that the carbon source is therefore being dosed solely in proportion to the flow rate. There are 2 ways to dose in proportion to the flow rate:

(a) using a Dosatron (https://www.dosatron.com/en, price: €500 – €1,000 ex. VAT)
(b) only dosing when influent is being pumped into the MBBR, using a classical membrane dosing pump. This does presuppose that the influent pump is always

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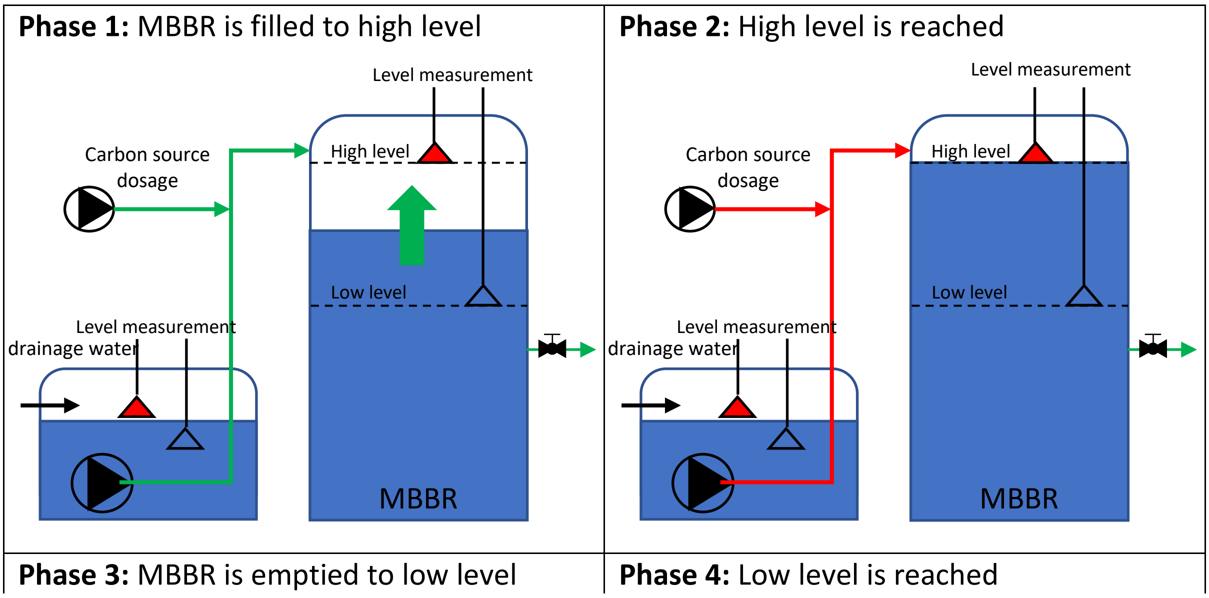
[x] Rusten, B., Hem, L. J., & Ødegaard, H. (1995). Nitrogen Removal from Dilute Wastewater in Cold Climate Using Moving-Bed Biofilm Reactors. *Water Environment Research*, 65-74.

pumping at its maximum flow rate or at a fixed, known flow rate of drainage water to the MBBR.

The second type of flow rate-proportional dosage has been applied at the testing facilities in Staden, Buggenhout, Putte and Onze-Lieve-Vrouw-Waver. The carbon source is dosed to the MBBR in the influent pipe's pressure line using a membrane dosing pump, type PKX Etatron Solenoid Dosing Pump type 0206 with a maximum flow rate of 2L/h at a pressure of 6 bar (https://etatron.co.uk/products/pkx-solenoid-dosing-pumps/ price: €260 ex. VAT).
To guarantee a constant flow rate to the MBBR, it is possible to feed the MBBR via a semi-batch method, whereby the water level in the MBBR is maintained between a high and a low level. The carbon source is only dosed once the MBBR has been filled with drainage water (Phase 1 in Figure 2). Once the high level in the MBBR has been reached, the influent pump stops pumping the drainage water (Phase 2 in Figure 2). At that point, the carbon dosing also stops until the minimum level in the MBBR is reached (Phase 3 and 4 in Figure 2). A valve is fitted on the MBBR's effluent pipe to regulate the MBBR's processing flow rate. This valve can then be manually opened to a greater or lesser extent to set the processing flow rate. The MBBR will therefore always go through a filling phase (which is accompanied by dosing the carbon source) and an emptying phase (without carbon dosing) every time. Depending on the flow rate of the influent pump that is pumping the drainage water to the MBBR, the dosing pump's flow rate will be set manually so that the carbon source is dosed to the drainage water in the right COD/NO_3-N ratio. This is easy to determine based on the daily mass flow rate of NO_3^- to be processed. Based on the desired COD/NO_3-N tatio (=8) and the maximum pumping rate of the membrane dosing pump (2L/h), the necessary quantity of carbon source can then be calculated for each specific one, through which the setting for the dosing pump can subsequently be determined (=% of the maximum rate). The calculation for setting the dosing pump for the Carbo ST carbon source has been integrated into the design tool developed in Excel (see 4.3).
For the level measurement/control, the pilot facilities (in Buggenhout, Putte and Onze-Lieve-Vrouw-Waver) are using a simple water level controller from the brand Toscano (https://www.toscano.es/en/product/th2/, price: €200 ex. VAT). The technical datasheet with a wiring diagram can be found in the appendix.



Phase 1: MBBR is filled to high level

Phase 2: High level is reached

Phase 3: MBBR is emptied to low level

Phase 4: Low level is reached

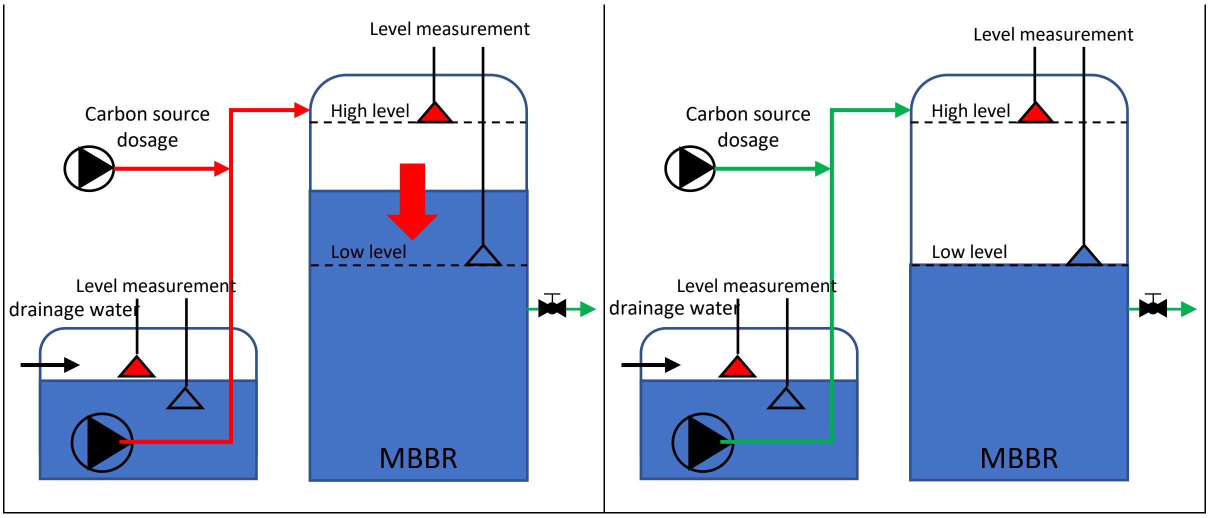


Figure 2: Regulation diagram for dosing the carbon source. Phase 1: Filling the MBBR; Phase 2: The high level in the MBBR is reached; Phase 3: The MBBR is emptied (no water is pumped from the drainage well to the MBBR); Phase 4: The low level in the MBBR is reached and the influent pump in the drainage well is activated. The red arrows indicate that no water is flowing in the applicable pipes; the green arrows show that water is indeed flowing towards or away.

Elaborate calculation example:

For the MBBR facility in Buggenhout, the settings of the PKX Etatron Solenoid dosing pump type 0206 must be determined based on the data below. The intention is to reduce a concentration of 150mg of NO_3^-/L to 0mg of NO_3^-/L. The MBBR facility in Buggenhout needs to be able to treat 0.5m^3 of drainage water per hour.

Max. Carbo ST pump flow rate	2	L/h
Max. drainage water pump flow rate	2	m^3/h
COD/N ratio	8	/
COD Carbo ST	1.5	kg of O_2/L
Carbo ST density	1.25	kg/L
Carbo ST price	0.865	€/kg

Based on the MBBR's flow rate and the average NO_3^-concentration, it is easy to calculate that the MBBR in Buggenhout must process 0.41kg of NO_3-N per day. If we assume an optimum COD/NO_3-N ratio of 8, this works out to a demand for 3.25kg COD/day. Taking account of the COD content of the Carbo ST carbon source of 1.5kg COD/L, the dose of Carbo ST per day will thus need to be 2.17L, which equates to a cost of €2.35 per day. To determine the percentage set for the dosing pump, the following calculations must be carried out:

- Calculation for the number of hours that the dosing pump doses the carbon source per day:

$$= \frac{MBBR\ processing\ rate\ (\frac{m^3}{h})}{maximum\ influent\ pump\ rate\ (\frac{m^3}{h})} .\,24\,h = \frac{0.5\,\frac{m^3}{h}}{2\,\frac{m^3}{h}} .\,24\,h = 6\,h$$

- Calculation for dosing pump setting:

$$= \frac{volume\ of\ Carbo\ ST\ dosage\ (L)}{max\ Carbo\ ST\ pump\ flow\ rate\ \left(\frac{L}{h}\right).} = \frac{2.17L}{2\,\frac{L}{h}\,.\,6\,h} = \mathbf{18\%}$$

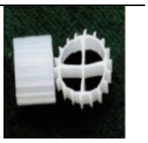
3 The carrier material

The carrier material used for the MBBR facilities is highly specific. It is best for the biofilm carriers to have the following distinguishing properties for optimum functioning:

(a) A large adhesion surface;
(b) many openings to allow water flow through the carrier;
(c) a large internal empty volume for the biomass to grow without clogging[xi];
(d) a density comparable to that of water (to improve the mixing of carriers in the reactor, amount to a 'moving bed');
(e) manufactured from a material resistant to wear and tear.

The role of the carriers is to maximise the biofilm surface and provide optimum conditions for the growth of the micro-organisms. A high specific surface makes high biofilm concentrations possible, characterising MBBR facilities by their small reactor volume. Typical biofilm concentrations are in the range of 3 000-4 000g TSS/m^3 (TSS stands for Total Suspended Solids). Moreover, the process' removal yield is commensurate with the biofilm surface, meaning the specific surface of the carriers is a very important parameter. The shape and size of the carriers play a major role in meeting the required surface and a good design is important for guaranteeing proper mass transfer[xii]. In general, the carriers are cylindrical, with a diameter of 1 to 3cm, and are equipped with internal and external fins to increase the specific surface.

Table 1: Dimensions and specific bulk surface of various MBBR carriers from the supplier Veolia.

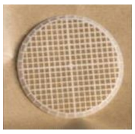
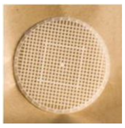
Supplier	**Name**	**Specific bulk surface[xiii]**	**Dimensions (depth, diameter)[xiii]**	**Photo of Carrier[xiv]**
Veolia Inc.	AnoxKaldnes$^{\text{TM}}$ K1	500m^2/m^3	7.2mm; 9.1mm	
	AnoxKaldnes$^{\text{TM}}$ K3	500m^2/m^3	12mm; 25mm	
	AnoxKaldnes$^{\text{TM}}$ K5	800m^2/m^3	4mm; 25mm	

[xi] Bjørn Rusten, Jon G. Siljudalen, Terje Andersen, Stephen Smith & Laura Marcolini. *Carrier element for purification of water,* WO 2012087151 A1, 2012.

[xii] cleanwaterops.com

[xiii] Bjorn Rusten, Bjørnar Eikebrokk, Yngve Ulgenes & Eivind Lygren. *Design and operations of the Kaldnes moving bed biofilm reactors*, Aquacultural Engineering 34, 2006, pp. 322-331./ cleanwaterops.com / http://www.paperindustryworld.com/moving-bed-biofilm-reactors/

[xiv] João Paulo Bassin, Márcia Dezotti. *Moving Bed Biofilm Reactor (MBBR),* Advanced Biological Processes for Wastewater Treatment, 13 September 2017, pp 37-74. / http://www.paperindustryworld.com/moving-bed-biofilm-reactors/ / http://technomaps.veoliawatertechnologies.com/mbbr/it/supporti.htm

AnoxKaldnes™ BiofilmChip (P)	900m^2/m^3	3mm; 45mm	
AnoxKaldnes™ BiofilmChip (M)	1,200m^2/m^3	2mm; 48mm	
AnoxKaldnes™ F3	200m^2/m	37mm; 46mm	
AnoxKaldnes™ O	300m^2/m^3	50mm; 60mm	

For the testing facilities in Staden, Buggenhout, Putte and Onze-Lieve-Vrouw-Waver, the decision was made to work with the AnoxKaldnes™ K5 carrier material (€1 300/m^3 ex. VAT) at the recommendation of the supplier Veolia Water Technologies. These carriers have a very large specific surface of 800m^2/m^3 of carrier material for biofilm adhesion. The larger the specific surface of the biocarriers, the larger the decomposition capacity per m^3 of MBBR volume can be.

3.1 Filling factor

One major advantage of the MBBR technology is that the volumetric filling factor (expressed in volume % carrier material of the total reactor volume) can be adapted to the specific situation and the desired capacity. According to Ødegaard et al.[xv], the performance of an MBBR is proportional with the total surface area of the biofilm (≅total adhesion surface of the carrier material). It is therefore easy to increase the capacity of an existing purification facility without increasing the footprint by building new tanks, but by simply adding more carriers. The maximum filling factor at which the carriers can still move freely in the reactor volume is 70%[xvi]. When an MBBR facility is started up, the best choice is to limit the filling factor to 30%, for example, so that it can be subsequently increased as necessary afterwards if the facility's capacity needs to be expanded. The testing facilities in Staden, Buggenhout and Onze-Lieve-Vrouw-Waver were equipped with AnoxKaldnes™ K5 carrier material, operating at a filling factor of 30%. The facilities' capacity can therefore still be expanded in the future by providing extra carrier material. We should point out that a higher filling factor makes the mixing of the carrier material more difficult.

[xv] Ødegaard Hallvard. *A road-map for energy-neutral wastewater treatment plants of the future based on compact technologies (including MBBR)*, Frontiers of Environmental Science & Engineering, 2016, 10(4): 02-02.
[xvi] Wisam Sabeeh Al-Rekabi. *Mechanisms of Nutrient Removal in Moving Bed Biofilm Reactors,* International Journal of Scientific & Engineering Research, January-2015, Volume 6, Issue 1, ISSN 2229-5518.

3.2 Aeration system and mechanical mixing apparatus

A certain turbulence needs to be provided in the MBBR to keep the carrier material in suspension, to achieve homogeneity, to increase the transport of the substrate (in this specific case, nitrate) to the biofilm and to retain a suitable biofilm thickness. Extremely high turbulence is not recommended, because the biofilm may then detach from the carriers. The increased friction and collisions between the bio-carriers may then give rise to a sharp reduction in biofilm thickness, leading to a loss of decomposition efficiency[xvi].

Turbulence in the MBBR can be obtained in two ways, depending on the type of process that needs to be carried out. If the process is aerobic, the mixture is obtained by injecting air via an aeration system from the floor of the MBBR tank (see Figure 3 (a)). If the process is anoxic or anaerobic, the mixing is provided by a top-entry mixer or a submerged mixer (see Figure 3 (b))[xvii]. Because heterotrophic denitrification is an anoxic process, it is recommended to work with a mixer instead of an aeration system to avoid excessive oxygen concentrations in the MBBR.

Normally, horizontal (banana) mixers with two or three shelves, fitted to a shaft, are used for heterotrophic denitrification at MBBR facilities. The mixers' maximum stirring speed is 120rpm (rotations per minute) to minimise damage to the bio-carriers[xviii]. Besides the type of mixer, the location where the mixer is placed in the reactor and the necessary mixer energy are important matters to consider in the design. Because the bio-carriers have a density that is lower than that of water (0.94 – 0.96g/cm^3 [xviii]), they float on the water's surface when no mixing energy is being added. Therefore the mixers need to be fitted just below the water's surface, with the mixer pointed towards the floor of the reactor at a 15-to-30-degree angle [xviii]. The mixer must not be placed too close to the water's surface to prevent oxygen dissolving into the water[xix]. The necessary mixing energy to keep the bio-carriers moving is generally 20 to 25W/m^3. When a low filling factor is applied, it may be possible to use a lower mixing energy down to a minimum of 10W/m^3.

[xvii] Rusten, B., Eikebrokk, B., Ulgenes, Y., & Lygren, E. (2006). Design and operations of the Kaldnes moving bed biofilm reactors. *Aquacultural engineering*, *34*(3), 322-331.

[xviii] McQuarrie, J. P., & Boltz, J. P. (2011). Moving bed biofilm reactor technology: process applications, design, and performance. *Water environment research*, *83*(6), 560-575.

[xix] https://www.bio-fil.es/facilities/design-considerations-mbbr/

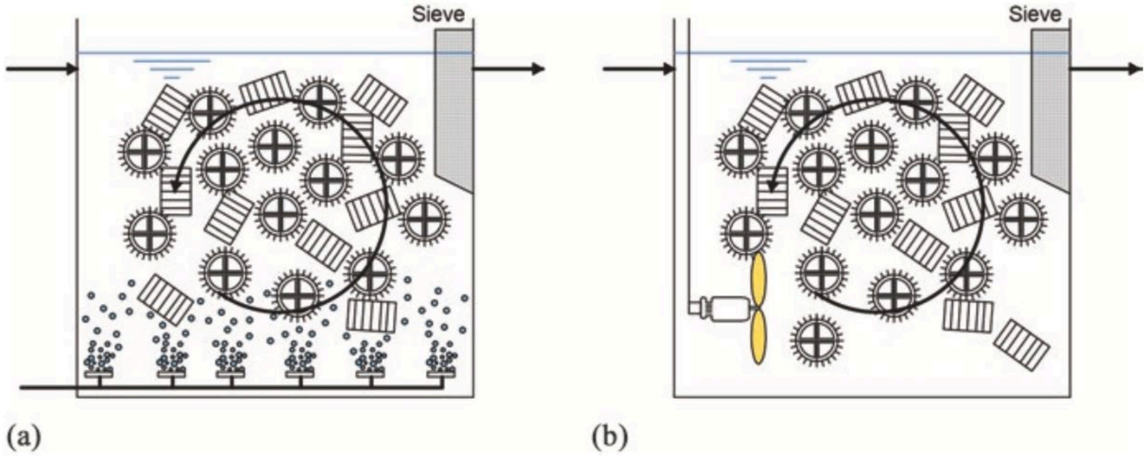


Figure 3: Principle of a moving bed biofilm reactor, MBBR: (a) Aerobic (aerated) reactor. (b) Anaerobic-anoxic reactor[xx].

Because MBBR facilities no larger than 15m^3 are used for the treatment of drainage water, the maximum mixing energy to be added is 375W. Suitable slow-running mixers powered on the order of maximum 375W are not commercially available. Therefore, an alternative method was needed to keep the bio-carriers moving in the MBBR. A mixer that may be eligible is the Mixer Flow 37S from AGUA (€2 200 ex. VAT). This is a stationary mixer with a rotation speed of 1 400rpm and powered at 370W. Although this mixer works at a very high rotation speed, the damage to the bio-carriers will most likely remain limited because the mixer's shelves are built into a stainless-steel cage, as can be seen in Figure 4 (a). As an alternative to a stationary mixer, periodically putting the reactor volume into motion via aeration can also be considered. Because heterotrophic denitrification is a biological process that takes place in the absence of oxygen, the aeration system must be operated such that an increase in dissolved oxygen concentration remains limited. It is therefore recommended to use coarse bubble aeration, which is characterised by poor oxygen transfer to the liquid and by only aerating periodically in very short time intervals. The pilot facilities (in Buggenhout, Putte, Onze-Lieve-Vrouw-Waver and Staden) are using a membrane disc aerator from ENVICON (6-8Nm^3/h, €50 ex. VAT), which is connected to an aeration pump from AquaForte type AP100 (6.4m^3/h, 65W, €200 ex. VAT) or AquaForte type AP150 (11.4m^3/h, 120W, €250 ex. VAT). The air pump is activated and deactivated with a timer switch (€150 ex. VAT), e.g., activated for 1 minute per hour or per 2 hours. The minimum air flow rate required to distribute the bio-carriers equally in the MBBR is in the order of 5 to 10m^3/m^2·h[xxi]. However, practical research has shown that an AP150 air pump connected to 2 ENVICON aeration discs can easily put the bio-carriers into motion in an MBBR reactor volume of 15m^3 (filling factor = 30%). An MBBR facility with a content of 15m^3 (= MBBR in Onze-Lieve-Vrouw-Waver) has an upper surface area of around 7m^2. An air flow rate of 1.6m^3/m^2·h therefore turns out to provide sufficient mixing that we have a 'Moving' Bed Biofilm Reactor in practice. To be able to make a comparison with mechanical mixers, the mixing energy can be calculated for this example too. By making use of an aeration system with membrane disc aerators, the mixing energy

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[xx] Dezotti, M., Lippel, G., & Bassin, J. P. (2018). Advanced Biological Processes for Wastewater Treatment. *Springer, İsviçre. doi*, *10*, 978-3.

[xxi] McQuarrie, J. P., & Boltz, J. P. (2011). Moving bed biofilm reactor technology: process applications, design, and performance. *Water environment research*, *83*(6), 560-575.

can remain limited to just 8W/m^3. We can therefore conclude that mixing via an aeration system is an economically attractive alternative to classical mixing via mechanical mixers. One important point for consideration is, of course, the adverse increase in the oxygen concentration in the MBBR. However, we see in practice that the oxygen concentration in the reactor only rises to a limited extent and that it very quickly drops back after the aeration is switched off, provided that sufficient carbon source (in excess) is present in the reactor.

(a) (b) (c)

Figure 4: (a) Mixer Flow 37S from Auga. (b) membrane aeration disc from ENVICON. (c) air pump from AquaForte type AP100/AP150.

4 Dimensioning of MBBRs

The hydraulic retention time (abbreviated to HRT and expressed in hours) is an important functional parameter of a denitrifying MBBR installation. The HRT will determine how large an MBBR needs to be to process a specific nitrate load. The necessary HRT is in turn determined by the maximum denitrification rate that can be guaranteed. The maximum denitrification rate is expressed in grams of NO_3-N that can be processed per m^2 of carrier surface and per day (g NO_3-N/(m^2.d)). This parameter itself depends upon the type of external carbon source, the carbon-nitrogen ratio (COD/N), the temperature of the water, the dissolved oxygen concentration and the bulk liquid macro-nutrient concentrations[xxii] (in which the phosphate concentration plays a major role). Assuming that we are always working with a surplus of carbon source, we can conclude that the water temperature plays a crucial role in processing drainage water. By considering the fact that the oxygen transfer must remain limited in the design of the MBBR, we can guarantee that the dissolved oxygen concentration is not a deal-breaker.

4.1 Influence of the water temperature on the denitrification rate

The water temperature plays an important role for the treatment of drainage water because the denitrification rate (expressed in g NO_3-N/(m^2.d) or g NO_3-N/(m^3.d)) depends strongly upon this parameter. Because drainage water mainly flow in the period from October to March, it may be the case that the water temperature drops to temperatures below 8°C during the winter months, which causes at least the halving of the denitrification rate compared to the reference denitrification rate at 20°C. This means that the necessary hydraulic retention time in the MBBR needs to be twice as long, so the necessary MBBR volume doubles as well.

[xxii] McQuarrie, J. P., & Boltz, J. P. (2011). Moving bed biofilm reactor technology: process applications, design, and performance. *Water environment research*, *83*(6), 560-575.

Denitrification can take place between 5 and 30° C. The temperature influences the growth rate of denitrifying organisms, as well as the reaction rate constants, with higher rates at higher temperatures. The temperature dependence of the reaction rate constants is described with the following adjusted Arrhenius equation:

$$k_T = k_{20} * \theta^{(T-20)}$$

With,
k_T= Denitrification rate at temperature T (g NO_3-N/(m^2.d) or g NO_3-N/(m^3.d))
k_{20}= Denitrification rate at 20°C (g NO_3-N/(m^2.d) or g NO_3-N/(m^3.d))
Θ= Temperature-activity coefficient / Arrhenius constant (-)
T= Temperature (°C)

The values of Θ in biological systems are between 1.02 and 1.25[xxiii]. Our own experimental research has shown that the Arrhenius constant is equal to a value between 1.069 and 1.072 and that a minimum denitrification rate of 1.0g NO_3-N/(m^2.d) (or, conversely, 800g NO_3-N/(m^3.d)) can always be guaranteed if the water temperature is 20°C and a sufficiently high COD/N ratio is guaranteed (the specific surface area of the AnoxKaldnes^{TM} K5 carrier material is 800m^2/m^3). The review work by McQuarrie and Boltz (2011)[xxiv] shows that a nitrate load of 1.0 to 2.0g NO_3-N/(m^2.d) is feasible for the design of post-denitrification MBBR installations. Figure 5 shows the design window for the nitrate load by the surface between both black curves (with Θ = 1.072). In addition, our own experimental results (●) and literature data (x) for the maximum denitrification rate at various temperatures have also been incorporated into this figure. Clearly, the design window for the nitrate load lies almost entirely below the maximum denitrification rates found in our own research and in scientific literature. Therefore, if a nitrate load within the design window at the minimum expected temperature is accounted for in the design of a denitrifying MBBR, then the MBBR will be capable of processing the entire nitrate batch and a high removal yield can be guaranteed (on the condition that the carbon source is present in surplus).

[xxiii] Metcalf & Eddy. *Wastewater Engineering, Treatment and Resource Recovery*, 5th Edition, Vol 1, Mc. Graw-Hill, International Edition, ch. 7.

[xxiv] McQuarrie, J. P., & Boltz, J. P. (2011). Moving bed biofilm reactor technology: process applications, design, and performance. *Water environment research*, *83*(6), 560-575.

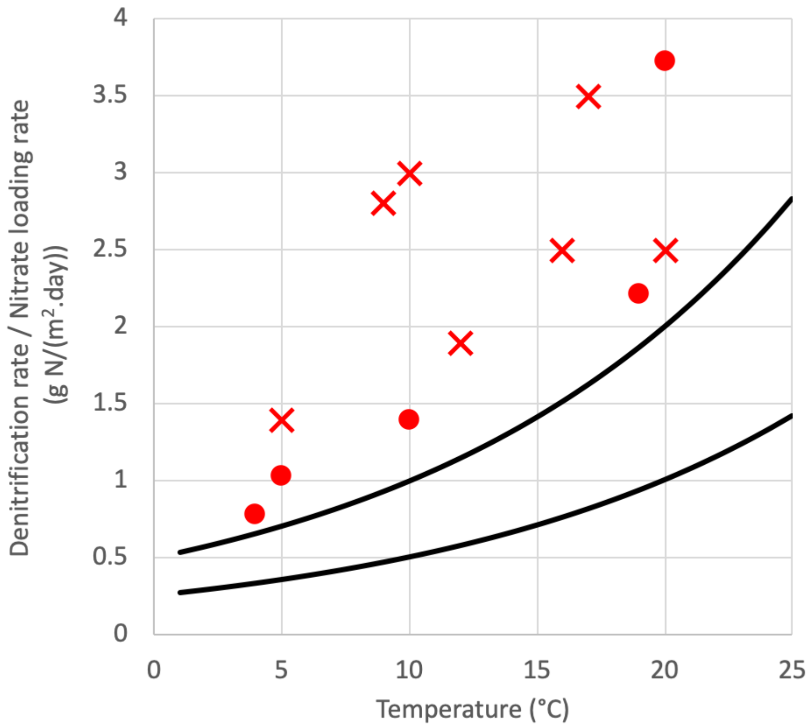

Figure 5: Denitrification rate or nitrate load for denitrifying MBBRs in line with the water temperature. The upper black line shows the minimum nitrate load for designing denitrifying MBBR facilities. The upper black line shows the maximum design load for a denitrifying MBBR. (•) Maximum denitrification rate in our own experimental research, (x) Maximum denitrification rate from literature data.

4.1.1 Choice for an aboveground or underground MBBR

The choice of an aboveground (built into a sea container) or an underground setup for the MBBR is mainly determined by the consideration whether the purification facility needs to be mobile. The major advantage of an underground MBBR is that the water temperature will always be higher than in an aboveground setup. In an underground MBBR, for example, it is possible to guarantee that certain parts of the facility will not freeze and that the water temperature will always be a few degrees higher than in an aboveground facility. In an aboveground facility, during cold winter months, certain pipes can freeze and the denitrification rate can be significantly reduced because the water temperature drops below 3°C. This situation does not occur in underground MBBR facilities, where water temperatures below 5°C are rather more exceptional. An additional advantage is that the pump height of the drainage pump can be lower than that in an aboveground MBBR. Conversely, one advantage of an aboveground MBBR is that the system is mobile and no excavation work is needed. Moreover, no environmental permit is required either.

4.1.2 Choice of a winter-proof carbon source

The experimental research by Bill et al. (2009)[xxv] evaluated the effectiveness of four different electron donors, e.g., methanol, ethanol, glycerol and sulphide (added as Na_2S), in moving bed biofilm reactors. This research clearly shows that a glycerol-based carbon source can

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[xxv] Bill, K. A., Bott, C. B., & Murthy, S. N. (2009). Evaluation of alternative electron donors for denitrifying moving bed biofilm reactors (MBBRs). *Water Science and Technology*, *60*(10), 2647-2657.

provide a good alternative to the classically used carbon sources, i.e., methanol and ethanol, at a relatively low water temperature of 12°C. We can clearly identify from the experimental work that glycerol and ethanol perform better than methanol and that the maximum denitrification rate for the three carbon sources are 1.9g NO_3-N/(m^2.d), 2.2g NO_3-N/(m^2.d) and 0.5g NO_3-N/(m^2.d), respectively. Our own research using respiration experiments has demonstrated that the commercially available glycerol-based carbon sources Carbo ST and Carbo BWB-60 are rapidly and almost 100% biodegradable (as opposed to molasses and BioAid = acetate-based carbon sources), which makes them eminently suited as carbon sources for denitrification (research carried out as part of the Master's dissertation by Elena Salzillo). Furthermore, a long-term experiment at lab-scale has also demonstrated that Carbo ST can even guarantee an average denitrification rate of 1.03 ± 0.22g NO_3-N/(m^2.d) at a water temperature of 5°C and an HRT of 8 hours (research carried out as part of the Master's dissertation by Stef Schietecatte). This value is well above the design window shown in Figure 5.

4.2 Influence of the phosphate concentration on the denitrification yield

When the phosphate concentration in the drainage water is too low, this can lead to a reduced removal yield for nitrate. The scientific publication of Andersson et al. (1998)[xxvi] describes how the dosage of phosphoric acid can greatly boost the denitrification rate in full-scale MBBRs. The supply of a limited quantity of phosphorus is necessary for the growth of the biomass on the carriers. This publication also demonstrates that the nitrate removal at an influent concentration of 0.1mg PO_4/L is only 70% of the removal yield using a phosphate concentration of 1mg PO_4/L. When the P:N ratio (PO_4-P-to-NO_X-N concentration ratio) is smaller than 0.000875, this indicates a phosphorus deficiency[xxvii]. For drainage water with a concentration of 150mg NO_3/L, this amounts to a minimum concentration of 0.03mg PO_4-P/L (=$\min C_{PO_4-P}$). If we assume that no phosphate is present in the drainage water, we can calculate how many mg PO_4-P need to be administered to the water per day (P demand) based on the daily flow rate to be processed. This daily dosage is calculated below for the MBBR in Buggenhout, which is treating a drainage flow rate of 12m^3/day (= $Q_{drainage}$).

$$\begin{aligned} P\ demand\left(\frac{kg\ PO_4-P}{day}\right) &= \frac{(\min C_{PO_4-P} - C_{PO_4-P})}{1000} * Q_{drainage} \\ &= \frac{\left(0.03\ \frac{mg\ PO_4-P}{L} - 0.00\ \frac{mg\ PO_4-P}{L}\right)}{1000\frac{L}{m^3}} * 12\frac{m^3}{day} \\ &= 0.000356\ kg\ PO_4-P/day = 356 mg PO_4-P/day \end{aligned}$$

The easiest way to achieve this dosage is to administer a quantity of phosphoric acid to the carbon source dosing vessel. The phosphorus source will then be administered at the same

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[xxvi] Andersson, B., Aspegren, H., Nyberg, U., la Cour Jansen, J., & Ødegaard, H. (1998). Increasing the capacity of an extended nutrient removal plant by using different techniques. *Water science and technology*, *37*(9), 175-183.

[xxvii] Boltz, J. P., Morgenroth, E., Daigger, G. T., deBarbadillo, C., Murthy, S., Sørensen, K., & Stinson, B. (2011). Process Control to Achieve Simultaneous Low-Level Effluent Nitrogen and Phosphorus Concentrations with Post-Denitrification Moving Bed Biofilm Reactor (MBBR) and Biological Active Filter (BAF) Systems. *Proceedings of the IWA/WEF Nutrient Recovery and Management*, 9-12.

time as the Carbo ST, proportional to the flow rate, as discussed in paragraph 2. Carbon source dosage. To find out exactly how many mL of phosphoric acid (m%=75%, density H_3PO_4 = 1.36kg/L) need to be added to the carbon source dosing tank (contents = 20L), the following calculation is valid:

$$Volume\ H_3PO_4 = \frac{P\ demand\left(\frac{kg\ P}{day}\right) * \frac{MW_{H_3PO_4}}{MW_P}\left(\frac{kgH_3PO_4}{kg\ P}\right) * 1000\left(\frac{mL}{L}\right)}{m\% * densityH_3PO_4\left(\frac{kgH_3PO_4}{LH_3PO_4}\right)} * \frac{Volume\ of\ Carbo\ ST\ vessel(L)}{Carbo\ ST consumptionper\ day\left(\frac{L}{day}\right)}$$

$$= \frac{0.000356\left(\frac{kg\ P}{day}\right) * \frac{97.994}{30.97}\left(\frac{kgH_3PO_4}{kg\ P}\right) * 1000\left(\frac{mL}{L}\right)}{0.75 * 1.36\left(\frac{kgH_3PO_4}{LH_3PO_4}\right)} * \frac{20(L)}{2.17\left(\frac{L}{day}\right)} = 10.2mL$$

The Carbo ST consumption per day (= 2.17L/day) was calculated in the calculation example for the MBBR in Buggenhout in 2. Carbon source dosage.

4.3 Design tool for MBBR facilities

Based on the obtained knowledge, a dimensioning tool was developed for making an estimation of the MBBR dimensions based on a limited amount of data of the drainage water. The project is making this Excel calculation module available to interested farmers and technology suppliers as an annex to this guide. The minimum data necessary for calculating the dimensions of an MBBR installation is:

(i) The influent nitrate concentration $\left(C^{IN}_{NO_3-N}\right)$ and the projected effluent nitrate concentration$\left(C^{EFF}_{NO_3-N}\right)$ expressed in mg NO_3-N/L,
(ii) The drainage flow rate that needs to be processed by the MBBR (Q) expressed in m^3/day,
(iii) The filling factor of AnoxKaldnes™ carriers type K5 $(\%K5)$ expressed in % and
(iv) The considered minimum water temperature (T_{min}).

In the first place, the mass flow rate of nitrate Q_{mass}, expressed in (kg NO_3-N/day), can be calculated.

$$Q_{mass}\left(\frac{QNO_{NO} - N}{day}\right) = \frac{\left(C^{IN}_{NO_3-N} - IN^{EFF}_{NO_3-N}\right)day}{1000}$$

Based on the mass flow rate of nitrate Q_{mass} and the minimum denitrification rate $\left(k_{T,MIN}\right)$ expressed in (g NO_3-N/(m^3.day)) that can be guaranteed at the projected minimum water temperature (T_{min}), it is then easy to calculate the MBBR volume in $m^3(V_{MBBR})$.

$$V_{MBBR}(m^3) = \frac{Q_{mass}}{k_{T,MIN} *\ \%K5} * 1000$$

Please note: this minimum denitrification rate depends on the temperature. For 6°C, for example, this is 302g NO_3-N/(m^3.day) or 0.38g NO_3-N/(m^2.day). The temperature dependence can be clearly derived from the graph on Sheet2 of the Excel design tool. To express the denitrification rate of g NO_3-N/(m^2.day) in g NO_3-N/(m^3.day), it must be multiplied by the specific surface of the Anox^{TM}K5 carriers (800 m^2/m^3). $k_{T,MIN}$ is calculated as follows based on a minimum denitrification rate of 1g NO_3-N/(m^3.day) at a water temperature of 20°C:

$$\begin{aligned} \mathrm{k_{T,MIN}} &= \mathrm{k_{20}} * \theta^{(\mathrm{T}-20)} = \ 1\,\mathrm{gNO_3} - \mathrm{N}/(m^2.day) * 1.072^{(T-20)} \\ &= \ 800\,\mathrm{gNO_3} - \mathrm{N}/(m^2.day) * 1.072^{(T-20)} \end{aligned}$$

This relationship between the denitrification rate and the temperature can also be found in Figure 5 (=bottom black curve). As can be identified in Figure 5, this builds in a sufficient safety margin for processing the nitrate content during the design of the MBBR. The minimum guaranteed denitrification rate as considered in the design is far below the denitrification rate as identified experimentally from our own research and literature data.

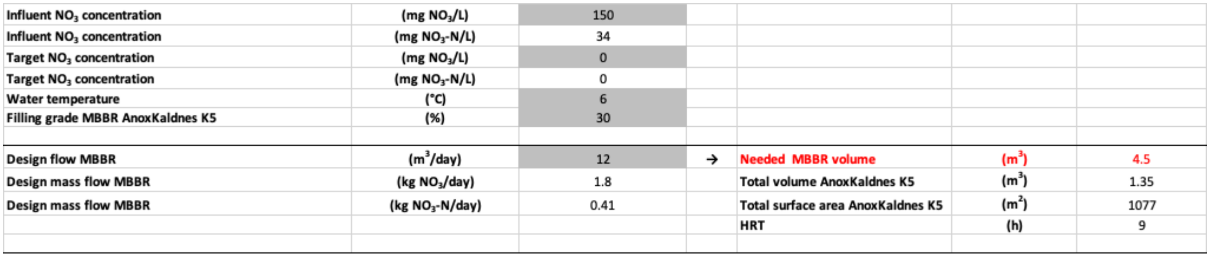
It is then easy to calculate the following parameters from this MBBR volume:

(i) The total AnoxKaldnes^{TM} K5 volume (m^3): $V_{K5} = \frac{Q_{mass}}{k_{T,MIN}} * 1000$

(ii) Total AnoxKaldnes^{TM} K5 surface (m^2): $A_{K5} = V_{K5} * 800\ m^2/m^3$

(iii) The hydraulic retention time (h): $HRT = \frac{V_{MBBR}}{Q}$

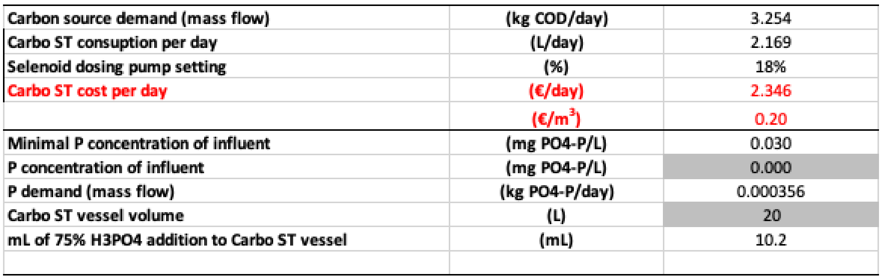
In the screenshot below (Figure 6) from the design tool, the example was developed from the Buggenhout MBBR, where a drainage flow rate of maximum 12m^3 per day must be processed with a concentration of 150mg NO_3/L. To achieve this, an MBBR volume of 4.5m^3 must be provided, assuming a minimum temperature of 6°C.



Influent NO_3 concentration	(mg NO_3/L)	150				
Influent NO_3 concentration	(mg NO_3-N/L)	34				
Target NO_3 concentration	(mg NO_3/L)	0				
Target NO_3 concentration	(mg NO_3-N/L)	0				
Water temperature	(°C)	6				
Filling grade MBBR AnoxKaldnes K5	(%)	30				
Design flow MBBR	(m^3/day)	12	→	Needed MBBR volume	(m^3)	4.5
Design mass flow MBBR	(kg NO_3/day)	1.8		Total volume AnoxKaldnes K5	(m^3)	1.35
Design mass flow MBBR	(kg NO_3-N/day)	0.41		Total surface area AnoxKaldnes K5	(m^2)	1077
				HRT	(h)	9

Figure 6: Screenshot of design tool for calculating the dimensions for an MBBR facility. The grey boxes are the data that need to be entered to calculate the mass flow rate, the volume of the MBBR and the AnoxK^{TM}5 carriers, and the HRT.

Based on the design, the quantity of the Carbo ST carbon source to be dosed per day and the setting for the dosing pump can also be calculated, as in the calculation example under Chapter 2 Carbon source dosage. In addition, the required amount of phosphoric acid, which needs to be added to the carbon source, can also be determined to guarantee that the previously mentioned P:N ratio is always respected. This calculation is based on the example calculation under Paragraph 4.2 Influence of the phosphate concentration on the denitrification yield. Figure 7 shows the calculations for the case in Buggenhout, from which we can derive that approximately 2 litres of Carbo ST must be dosed per day, meaning that the dosing pump must be set to 18%. To guarantee the P:N ratio, around 10mL of phosphoric acid must be administered to each 20L vessel of carbon source.



Carbon source demand (mass flow)	(kg COD/day)	3.254
Carbo ST consuption per day	(L/day)	2.169
Selenoid dosing pump setting	(%)	18%
Carbo ST cost per day	(€/day)	2.346
	(€/m^3)	0.20
Minimal P concentration of influent	(mg PO4-P/L)	0.030
P concentration of influent	(mg PO4-P/L)	0.000
P demand (mass flow)	(kg PO4-P/day)	0.000356
Carbo ST vessel volume	(L)	20
mL of 75% H3PO4 addition to Carbo ST vessel	(mL)	10.2

Figure 7: Screenshot of design tool for calculating the flow rate of the carbon dosage and the addition of the phosphorus source to achieve a sufficiently high nitrate removal yield. The grey input boxes must be completed by the user to be able to make the calculation.

5 FAQ

5.1 How is it best to start up an MBBR and how long does the start-up period take?

When starting up an MBBR installation, it is best to begin with a full tank of drainage water rich in nitrate. A surplus of carbon source and a limited quantity of phosphoric acid is administered to this, such that the P:N ratio (PO_4-P-to-NO_X-N concentration ratio) is a minimum of 0.000875 and the COD:N ratio is a minimum of 10. For an initial start-up of an MBBR, it is best to ensure that a limited proportion of the AnoxKaldnes^{TM} carrier material (type K5) already contains a fully grown denitrification biofilm (e.g., 100L of carrier material from a well-functioning denitrifying MBBR) or that activated sludge is being injected at start-up. It is best to set the flow rate at 25% of the MBBR's maximum capacity at the start. A minimum start-up period of 3 to 4 weeks should be considered to obtain a full denitrifying biofilm on the carrier material. This start-up period only applies to the initial start-up. When the installation doesn't process drainage water for several weeks/months after its first drainage season, the restart is much quicker than during the initial start-up. After 1 to 2 weeks, the denitrification activity in the MBBR will have been largely restored. The latter has been confirmed both through pilot tests at lab-scale and in the field.

5.2 What are the most common problems that occur when operating an MBBR and what are the solutions to these?

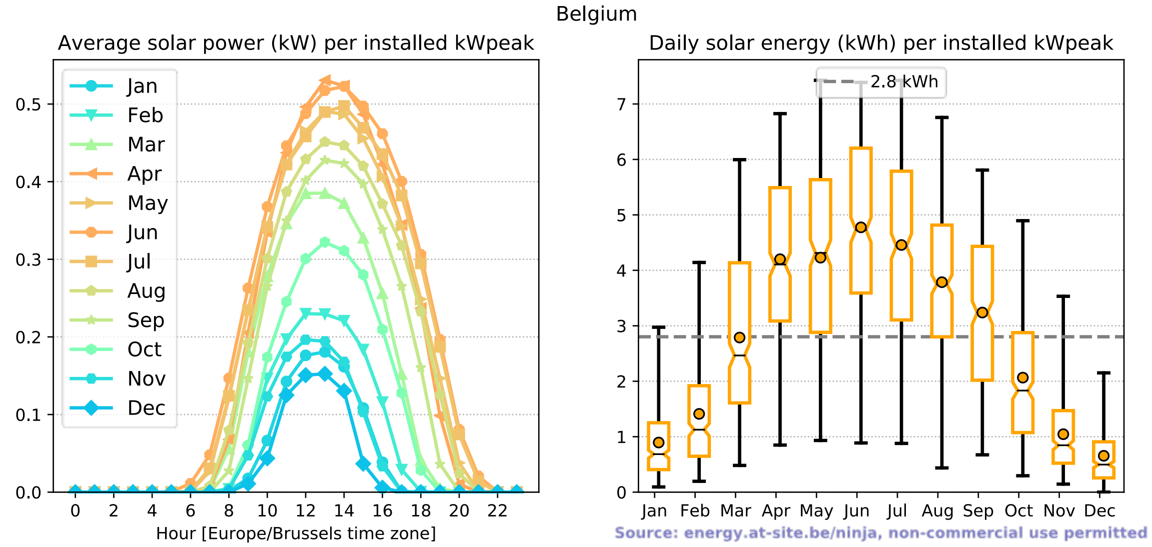
Practical experience of operating MBBR facilities in the field has shown that most problems can be related back to the dosage of the carbon and/or phosphorus source. A reduced removal yield often points to the fact that the carbon/phosphorus source tank is empty, the dosing pump had been set wrong or that there was an obstruction in the dosage piping to the MBBR. A lower processing rate is another common issue, whereby a large proportion of the drainage flow rate cannot be processed. If the flow rate from the drainage pump to the MBBR is too low or has dropped off completely, it is best to check the following things: (i) the supply pipe to the MBBR (is this blocked?), (ii) the level sensors in the MBBR (are the level sensors correctly positioned?), (iii) the valve at the overflow to the receiving surface water stream (has this valve been partially or fully closed?).

5.3 What are the consequences of overdosing the carbon source for the COD concentration in the receiving surface water stream?

The issue of overdosing the carbon source and the consequences for the COD values in the receiving surface water stream and the MAP measurement point were studied during the pilot test in Onze-Lieve-Vrouw-Waver. Where a COD:N ratio of 10 was maintained in the MBBR at this location, we could identify that there was a rise in the carbon concentration in the MBBR's effluent. The overdose raised the TC (Total Carbon) value of 14±1mg C/L in the drainage water to 226±82mg C/L in the MBBR's effluent, from which we could conclude that a quantity of carbon source had ended up in the receiving water stream. In the same period (January 2019), samples were also taken in the receiving water stream and at the MAP measurement point downstream from the drainage pipe. It was possible to demonstrate that there had been no increase in the carbon content in the water stream by comparing the samples with others taken downstream and with the TC concentration of the drainage water. The average concentration measured in the water stream and at the MAP measurement point was 14±4mg C/L. The explanation for this is partly that the MBBR's effluent water is diluted when it gets to the water stream and that the carbon source is further decomposed by anoxic processes in the receiving surface water stream.

5.4 What if there is no electricity available at the drainage pipe location? Does an off-grid facility with a battery pack and photovoltaic solar panels provide a solution?

Two possible solution strategies were investigated in the project when no electricity is present at the drainage pipe location. There was an initial review into whether an off-grid facility with a battery pack and photovoltaic solar panels could produce and store sufficient energy to operate an overground MBBR during the winter months. This off-grid approach was comprehensively tested during the pilot test in Buggenhout and Staden. For an overground MBBR that can process a drainage flow of $12m^3$ to $48m^3$, 0.8 to 2.8kW of daily electrical energy needs to be provided for pumping the drainage water up to the MBBR, dosing the carbon and phosphorus source and mixing via a recirculation pump and/or aeration pump. In order that an estimate could be made of the daily electricity yield from photovoltaic solar panels, the data from the graphs below in Figure 8 was used.

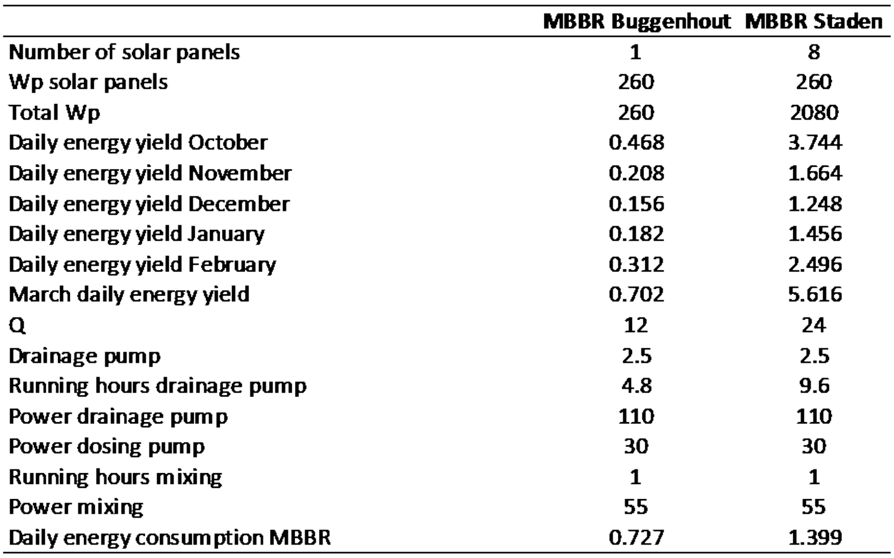


Data source: renewables.ninja CC BY-NC 4.0, doi: 10.2016/j.energy.2016.08.060
CM-SAF SARAH solar model, years 2005-2015

Figure 8: Average power and energy generated per installed kW peak in photovoltaic solar panels.

The Buggenhout MBBR was equipped with 1 photovoltaic solar panel (260Wp) and a 50Ah Li-ion 24V battery for energy storage. The MBBR in Staden's off-grid system contains 8 photovoltaic solar panels (2,080Wp) and two 100Ah Li-ion 24V batteries that are charged up alternately, so as to be able to better span periods without light. The calculations below were carried out for both off-grid systems.

Table 2: Calculation for daily energy yield from the photovoltaic solar panels and the energy consumption for both off-grid facilities in the field (Buggenhout and Staden).



	MBBR Buggenhout	MBBR Staden
Number of solar panels	1	8
Wp solar panels	260	260
Total Wp	260	2080
Daily energy yield October	0.468	3.744
Daily energy yield November	0.208	1.664
Daily energy yield December	0.156	1.248
Daily energy yield January	0.182	1.456
Daily energy yield February	0.312	2.496
March daily energy yield	0.702	5.616
Q	12	24
Drainage pump	2.5	2.5
Running hours drainage pump	4.8	9.6
Power drainage pump	110	110
Power dosing pump	30	30
Running hours mixing	1	1
Power mixing	55	55
Daily energy consumption MBBR	0.727	1.399

From the results of the pilot test in Buggenhout, it was determined that, during darker periods (short, overcast days during the winter months), only 21% of the design flow rate of the drainage water (3m^3/day) could be treated by the MBBR in the month of December. By fitting more photovoltaic panels and working with two batteries that are alternately charged up, it was possible to drive up this percentage considerably at the pilot facility in Staden to 89% (21m^3/day). The summary graph below clearly shows that the off-grid system for the MBBR facility in Staden is better attuned to the darker winter months. For the MBBR in Buggenhout, the design flow rate can only be maintained with the solar panel provided in the month of April. Only the dark days in December are a problem for the MBBR in Staden.

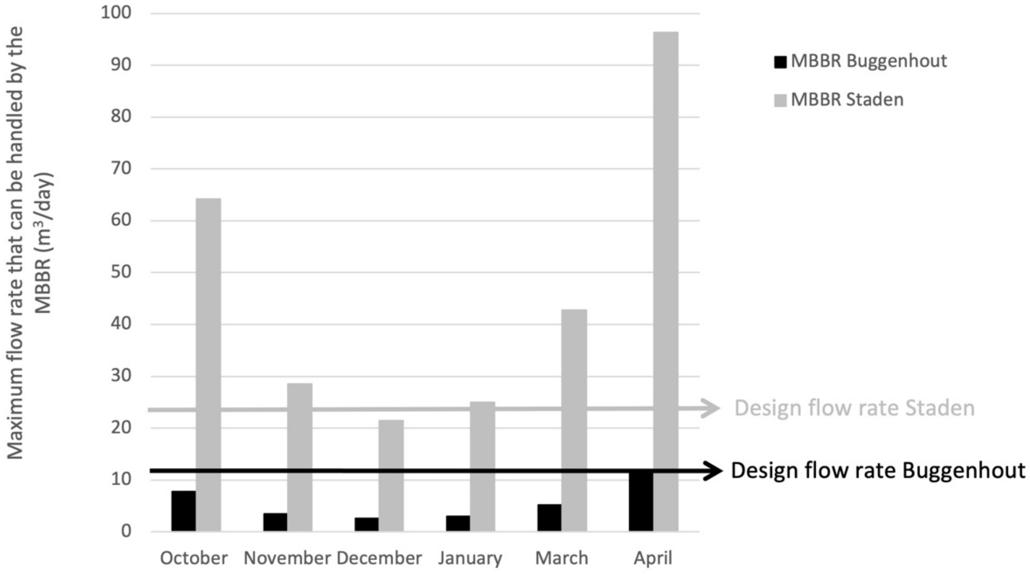


Figure 9: Calculated maximum flow rates that can be processed based on the electrical energy generated by the photovoltaic solar panels for the MBBR facilities in Buggenhout and Staden.

A second alternative for the electricity supply was also reviewed specifically for the case study in Buggenhout. Because the facility is located just two hundred metres from the closest tail end (Brandstraat, 9255 Buggenhout), running a classical electricity cable from the tail side to the MBBR facility is one possible solution that is economically feasible. The cost associated with purchasing a small junction box and electricity cable can be estimated at 3,000 euros. Naturally, this option also provides the certainty that the drainage flow rate can be processed totally at any time.

5.5 Drainage water often contains very little to no phosphates. Does phosphorus need to be dosed to guarantee proper operation of the MBBR?

For this question, we refer to Paragraph 4.2 in this guide, which discusses the influence of the phosphorus concentration on the denitrification yield. Where the P:N ratio (PO_4-P-to-NO_X-N concentration ratio) is smaller than 0.000875, this is known as a phosphorus deficiency and the growth of the denitrifying biomass will be hampered, with disastrous consequences for the denitrification efficiency. Specifically for drainage water, this means that the concentration of phosphorus in the drainage water needs to be around 0.3mg PO_4-P/L. In many cases, this means that extra phosphorus needs to be dosed for the growth of the denitrifying biomass. This is best done by dosing phosphorus along with the carbon source. Based on the calculations in Paragraph 4.2 we concluded that around 10mL of phosphoric acid needs to be administered to 20L of Carbo ST carbon source in order to be able to guarantee the P:N ratio in the drainage water of 0.000875.

5.6 What could be behind a reduction in an MBBR's nitrate removal yield?

The following parameters could be behind a reduced nitrate removal yield: (i) too low water temperature, (i) too low dosage of carbon and phosphorus source, (iii) too high oxygen concentration / redox potential in the MBBR, (iv) too high processing flow rate, resulting in a too low hydraulic retention time (HRT).

5.7 What online sensors are available on the market for monitoring an MBBR facility and what is the potential use of these sensors?

Online sensors that can be useful in denitrifying MBBR facilities are online nitrate, redox and pH sensors. Because the selected carbon source Carbo ST (glycerol-based) does not immediately cause a sharp rise in pH, it is not necessary to equip a denitrifying MBBR with a pH sensor. Nitrate sensors, on the other hand, could be a useful tool for monitoring an MBBR's denitrification functioning over time. Disadvantages associated with online nitrate sensors are the high investment and operating cost and the need for regular calibration. Experimental data obtained from the pilot facility in Onze-lieve-Vrouw-Waver and Putte and the pilot facility at lab-scale has shown that the redox potential (ORP) is a good parameter for assessing the proper functioning of a denitrifying MBBR and gives a good indication of whether the denitrification process is running well or poorly. If the redox potential is lower than -150mV, we can guarantee that a sufficiently high denitrification speed is being maintained. If redox potentials below -300mV are reached, we can state that sufficient denitrification has been achieved. A shortage of carbon source or too low water temperatures will quickly lead to a rise of the redox potential. Although an online redox sensor can give you a good idea of the facility's proper functioning, it remains recommended to conduct an on-site inspection and carry out the necessary maintenance of the facility.

A price indication is given below for industrial sensors that are made for water purification applications:

- pH sensor: €700 ex. VAT
- ORP sensor: €700 ex. VAT
- Nitrate sensor: €3,000 + €750/year for replacing sensor cap
- Transmitter for connecting 2 online sensors: €1,650 ex. VAT

5.8 What is the ideal way to monitor and maintain an MBBR and what are the most important tasks to be carried out on a regular basis?

A properly functioning denitrifying MBBR requires little monitoring or maintenance. It is a robust system that requires only brief monitoring every week. During this weekly check-up, which is perfectly possible by the farmer, the following things need to be checked: (i) Reading the litre counter to record the weekly volume processed by the MBBR. (ii) Checking the carbon source volume and the proper functioning of the dosage. (iii) Taking any samples for analysis or checking of denitrification functioning via test strips. (iv) Noting the temperature and redox potential if online sensors are present.

5.9 What are the most important suppliers of technology and products/chemicals regarding MBBR facilities?

Supplier of:	Specific products	Company name:	Address:	Contact:
Carbon source	Carbo ST and Carbo BWB	Melspring International BV	Arnhemsestraatweg 8, 6881 NG VELP (GLD), The Netherlands	Hans Neuteboom +31(0)26 384 200
Phosphorus source + pumps	Phosphoric acid	Van Dessel Automatisatie	Drevendaal 2 2860 Sint-Katelijne-Waver, Belgium	Paul Van Dessel +32(0)15 320 730
MBBR technology	MBBR and K5 carrier material	Veolia Water Solutions and Technologies Belgium	Esperantolaan 5, 3300 Tienen, Belgium	Kris Lambert + 32(0)16 78 16 20
MBBR technology	MBBR	PureBlue Water	Gentsevaart 21,	Angelo de Mul

			4565ER Kapellebrug, The Netherlands	+31(0)114 32 10 20
Online sensors	Online sensors	Hach Lange	Motstraat 54, 2800 Mechelen, Belgium	Frank Demey +32(0)15 42 35 00

5.10 What about potential production of laughing gas during the denitrification process?

When operating the denitrifying MBBRs, it is also necessary to minimise the production of laughing gas (N_2O) during the denitrification process. As with any technology based on denitrification, laughing gas may be able to escape from the denitrifying MBBR when the denitrification does not run efficiently. Low COD:N ratios, oxygen concentrations higher than 0.4mg O_2/L and low pH values (< 7.5) may lead to a rise in N_2O production during the denitrification process (Hanaki et al., 1992[xxviii]; Tallec et al., 2006[xxix], Tallec et al., 2008[xxx]). With these preconditions in mind, the full-scale MBBR facilities can be operated at low N_2O levels with no problems.

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