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Research article

Membrane aerated biological reactors (MABRs) to enhance the biological treatment process at a WWTP

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ABSTRACT

The goal of climate neutrality, under the provision of the European Green Deal, will require great efforts to wastewater treatment plants (WWTPs) to reduce and optimize their energy consumption. The utilization of membrane aerated biological reactors (MABRs) to renovate existing WWTPs could be an opportunity in this sense. In this study, the control of the flow at the outlet of a pure, open-end MABR was used as a strategy to minimize the oxygen consumption and obtain high oxygen transfer efficiencies (OTEs). OTE values of more than 80% were observed, which are not so common in the literature and are comparable to those obtained with a close-end configuration. High efficiencies (85%) were found for the removal of both COD and total nitrogen from samples of real wastewater. A techno-economic analysis, comparing a conventional activate sludge (CAS) plant with a MABR, both with a treatment capacity of 25,000 equivalent inhabitants (e.i.), found that the MABR only needed approx. 1/5 of the energy required by the CAS. A MABR plant could become a profitable investment, under a fixed return time of 5 years, compared to a CAS with a CAPEX of 123.7 k€, if the overall cost of the cassettes was inferior to 237 k€. A sensitivity analysis imposing a variation of ±50% on the input parameters (cost of blower, diffusers, electric energy, and opportunity cost of capital) demonstrated that the cost of electric energy had the highest impact on the maximum allowable value of the MABR investment, which was affected by ± 26% with respect to the value calculated in the reference scenario.

1. Introduction

The sector of urban wastewater treatment can have a significant role in reducing greenhouse gases (GHGs) emission and, consequently, achieving the goal of climate neutrality under the provision of the European Green Deal. The recent (January 2024) revision of the urban wastewater treatment directive requires that municipal wastewater treatment plants (WWTPs) target energy neutrality by 2045 (Urban wastewater: Council and Parliament reach a deal on new rules for more efficient treatment and monitoring - Consilium (europa.eu). The more efficient use of energy and the reduction of energy consumptions in WWTPs can help to achieve this goal (Campo et al., 2023).

According to the most recent data published by the International Energy Agency, the water sector globally uses approx. 120 Mtoe per year, 4% of the global energy consumption, almost as much the energy used by Australia (IEA, 2018). The energy share of WWTPs accounts from 15 to 25% of the water sector (Rani et al., 2022). Most of the municipal WWTPs include a section of biological treatments, where organic substances and nutrients are removed with energy-intensive processes, such as conventional activated sludge (CAS) plants. Typical values of oxygen transfer efficiencies (OTEs) in CAS are still at very low values, in the order of only 10–15%, which makes CAS an unsustainable method for wastewater treatment (Guven et al., 2023). The achievement of energy neutrality at a WWTP requires an improvement in oxygen utilization, with a consequent energy saving in the section of the biological treatments (Maktabifard et al., 2018).

MABR is a novel technology, primarily developed to both increase the efficiency in oxygen utilization and save space at wastewater treatment facilities (Syron et al., 2015). MABR uses air permeable membranes to both supply oxygen and offer a support for the development of an attached biomass (Li et al., 2023c). Differently from the traditional attached biomass systems (namely moving bed biofilm reactor (MBBR), rotating biological contactors (RBC) or trickling filters), MABR is a counter diffusional system. The inner surface of the membrane is exposed to the air, which diffuses from the membrane lumen out through the biofilm (Syron and Casey, 2008). Conversely, the outer

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surface is exposed to the wastewater, from which substrates, such as organic substances and ammonia nitrogen (NH_4^+-N), diffuse from the liquid bulk towards the biofilm (Siagian et al., 2024).

The utilization of MABRs, instead of traditional air diffusers, to revamp existing WWTPs must be supported by technical and economic feasibility assessments. The most relevant parameters affecting the above-mentioned two sides of a project sustainability are the OTE and the oxygen transfer rate (OTR). The OTE has an evident effect on the volume of air to be supplied to the biological process and, consequently, on the power of the air blower and energy expenditure (Elsayed et al., 2021). The OTR impacts on the extension of the surface area of the membrane to be installed and, consequently, on the purchase and installation costs (Castrillo et al., 2019).

In MABRs, the attached biofilm acts as a catalyzer in the transfer of oxygen, which crosses the biofilm without passing through the liquid phase boundary layer, thus guaranteeing high oxygen utilization rates (Pellicer-Nàcher et al., 2013; Aydin et al., 2021). The so-called dead-end operating mode (that is the absence of venting in the membrane lumen) proved to be capable of generating OTEs close to 100% (Tian et al., 2020). However, such an operating mode is hardly applicable in real plants, because gases generated by microbial metabolism (e.g. CO_2 and N_2) can back diffuse and reduce the transfer of oxygen (Li et al., 2023a).

A recent study, which made use a hybrid configuration (i.e. incorporation of MABR modules into the anoxic zone of CAS plants), demonstrated that the highest OTE values could be achieved working at low airflows, with no impact on the OTRs (Uri Carreño et al., 2021). Concurrently, it was found that high values of the OTR were strongly correlated with the NH_4^+-N load. Airflow has a significant effect also on the OTR, especially at low operating pressures (Bunse et al., 2020). Hybrid configurations were deemed of interest for the retrofitting of existing plants, because of its capacity of providing an additional nitrification capacity (Corsino and Torregrossa, 2022). Telles Silveira et al. (2022), using a pilot plant in the same configuration and working with a high strength wastewater and summer temperatures, obtained very promising values of both nitrogen removal (3.7 g NH_4^+-N/m^2·d) and OTR (approx. 20 g/m^2·d), and acceptable OTEs, with the highest value at 53%. Conversely, experiences involving pure MABR (that is, in the absence of suspended biomass) are rarer. Ravishankar et al. (2022) monitored the removal of tCOD and total nitrogen (TN) over two summer and two winter seasons in a pilot-scale (12 m^3) MABR, installed in a Spanish WRRF. They observed high COD and TN removal, especially during the summer season, at 80% and 92%, respectively, but did not provide information concerning OTE and OTR values.

Working at high OTEs allows the MABR aeration efficiency to reach values of up to 6–8 kg O_2/kWh, that is 4–5 times more than CAS using air diffusers (Li et al., 2023b). Furthermore, savings up to 200 US$/1000 m^3 of treated water could be achieved, depending on the costs of membrane and electric energy (Aybar et al., 2014). However, a literature search carried out in the Scopus database using the keywords “MABR” & “cost” did not provide more recent studies considering economic aspects in the utilization of MABR for new plants or for revamping of existing ones.

This work has two innovative features:

First, in all the studies reported above, MABRs were fed at a fixed inlet air flow rate. Such an operating condition does not allow to use oxygen at high efficiencies. In this study the control of the flow at the outlet of the MABR was employed as a strategy to obtain high OTE values; Second, techno-economic analyses on MABRs are not so common, as demonstrated by the literature search carried out in the Scopus database.

Specifically, this study was carried out in three phases. In the first phase, tests with a pure, open-end MABR and synthetic wastewater were performed at variable values of airflow to optimize the OTE. The control of the flow at the outlet of the MABR was used as a strategy to obtain high OTE values. In the second phase, the operating conditions defined in phase (i) were used to assess the efficiency of the MABR in COD and TN removal from streams of real wastewater coming from a municipal WWTP. Values of the OTR and contaminant removal fluxes (i.e. specific nitrification and denitrification) were determined as well. In the last phase (phase iii), an assessment of the MABR economic viability was carried out. Two scenarios were compared, in which either a conventional aeration process via fine-bubble diffusers or MABR cassettes were employed to renovate the biological section of a WWTP with a treatment capacity of 25,000 equivalent inhabitants (e.i.). The economic comparison was carried out using the Discounted Cash Flow (DCF) approach with the purpose of identifying the greatest value of the initial investment for the MABR that could compensate the higher cash outflows of the CAS plant, due to the greater energy consumption. A sensitivity analysis was finally performed with the aim of assessing the relative importance of the input parameters, namely the unit cost of a blower, the cost of diffusers, the cost of energy and the opportunity cost of capital, on the maximum allowable MABR initial investment.

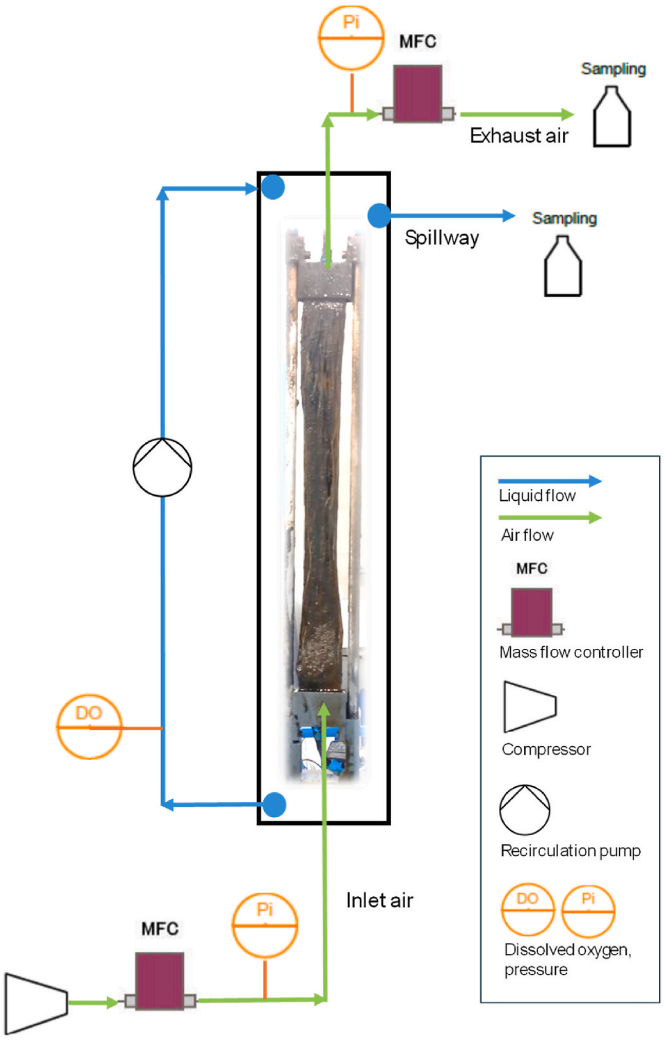

Fig. 1. Schematic diagram of the experimental set-up.

2. Materials and methods

2.1. Reactor set-up

The set-up used for the tests, which will be described in Sections 2.2 and 2.3, is shown in Fig. 1. It included a ZeeLung lab-scale module (SUEZ Water Technologies and Solutions), a plexiglass rectangular-section reactor with a working volume of 3 L, in which the module was installed, a 25-L oil-free compressor (AirCLEAN) for feeding air to

Table 1
Detail of the experimental conditions of Phase 1.

Period	Duration (d)	HRT (d)	Off-gas flow rate Q_{OUT} (Nm^3/h)	OLR (kg COD/ $m^3{\cdot}d$)	NLR (kg N/ $m^3{\cdot}d$)	PLR (kg P/$m^3{\cdot}d$)
1	20	10	1.000	0.48	0.17	0.12
2	20	10	0.250	0.47	0.16	0.12
3	20	10	0.125	0.47	0.18	0.13
4	20	10	0.078	0.47	0.18	0.13

the membrane, a peristaltic pump for feeding the liquid flow and a membrane pump for the liquid flow recirculation into the reactor. The module has a surface area of 0.25 m^2 of medium available for biofilm growth, thereby resulting in a surface-to-volume ratio of 83.3 m^2/m^3. Each module is formed by cords with a diameter of 0.7 mm and a length of 1 m. The cord structure consists of a braided polyester support, surrounded by a number of filaments (lumens).

The air was supplied from one end at 30 kPa, while the opposite end was open to the atmosphere in an open-end configuration. The pressure of the air at the inlet of the module was fine-tuned through a manual pressure reduction. Several apparatuses for the measurement and control of the operating parameters completed the set-up, specifically: a gas mass-flow meter and a controller installed in the air inlet pipe for the measurement of the airflow entering the module; a gas mass-flow meter and a controller (0–2 NL/h, red-y, Vögtlin Instruments GmbH) in the air outlet pipe to set and control the rate/pressure of the airflow leaving the module; a gas analyzer (Micro GC Fusion ® INFICON) for the detection of O_2, CO_2, N_2 and CH_4 in the outlet airflow.

The reactor was seeded with a secondary sludge collected at the SMAT WWTP located in Castiglione Torinese (North-West Italy, 2 M p.e., population equivalent). Upon formation of the membrane biofilm, the experimental operations were carried out in two phases, namely Phase 1 and Phase 2, described in Sections 2.2 and 2.3.

2.2. *Reactor operation – Phase 1*

Phase 1 was aimed at identifying the operating conditions which allowed maximum values of OTE and efficiency in the utilization of the oxygen supplied to the reactor (that is the oxygen utilization efficiency, OUE). In Phase 1 the membrane was continuously supplied with air, and the reactor was fed with synthetic wastewater in a fed-batch mode. The synthetic wastewater was prepared by mixing amounts of tri-hydrated sodium acetate ($CH_3COONa{\bullet}3H_2O$) and di-ammonium phosphate ($(NH_4)_2HPO_4$) to deionized water to obtain the organic (OLR), nitrogen (NLR) and phosphorous (PLR) loading rates shown in Table 1. The values were fixed to simulate the characteristics of an urban wastewater with a high nutrient load.

The test lasted 80 days and was divided into 4 periods of 20 days each, as detailed in Table 1. Specifically, with the aim of obtaining high OTE values, the airflow was fixed at the outlet of the reactor (at 4 decreasing values, namely 1.000, 0.250, 0.125 and 0.078 Nm^3/h) and it was consequently measured at the inlet.

From the liquid side, a volume of synthetic wastewater equal to 300 mL, that is Vr (volume of the reactor)/HRT (fixed to 10 days) was extracted, and a new volume was fed every day, from Monday to Thursday. On Friday the volume of the wastewater extracted and fed to the reactor was triplicated, in order not to deprive the biomass with the substrate during the weekend.

The oxygen utilization rate (OUR), that is the amount of the oxygen supplied to the MABR and consumed by the biological process (g/d), was calculated as in Equation (1)

$$OUR = Q_{IN} \bullet 0.209 - Q_{OUT} \bullet [O_2]_{OUT} - \frac{V_R}{HRT} \bullet \left[\overline{O_2}\right] \quad (1)$$

Table 2
Composition of the wastewater samples fed to the MABR.

Sample	tCOD (mg/L)	sCOD (mg/L)	TSS (mg/ L)	VSS (mg/ L)	NH_4-N (mg/ L)	NO_3-N (mg/ L)	NO_2-N (mg/ L)
1	200	67	NA	NA	30	0.24	0.57
2	220	76	142	88	30	ND	ND
3	188	80	178	100	32	0.36	ND
4	240	98	182	111	44	0.22	ND
5	220	72	127	77	35	0.29	ND

NA: not available; ND: not detected.

The OUE was consequently calculated as in Equation (2)

$$OUE = \frac{OUR}{Q_{IN} \bullet 0.209} \quad (2)$$

The OTE (%) was calculated as in Equation (3)

$$OTE = \frac{Q_{IN} \bullet 0.209 - Q_{OUT} \bullet [O_2]_{OUT}}{Q_{IN} \bullet 0.209} \quad (3)$$

The OTR (g $O_2/m^2{\bullet}d$) was calculated as in Equation (4)

$$OTR = \frac{Q_{IN} \bullet 0.209 - Q_{OUT} \bullet [O_2]_{OUT}}{A_M} \quad (4)$$

where: Q_{IN} and Q_{OUT} were the airflow entering and exiting from the MABR, respectively; 0.209 was the volumetric concentration of oxygen in the inlet airflow, which was assumed equal to 20.9% (v/v); $[O_2]_{OUT}$ was the measured volumetric concentration of oxygen in the outlet airflow; $\left[\overline{O_2}\right]$ was the concentration of dissolved oxygen (DO) into the bulk liquid; A_M is the membrane surface area, that is 0.25 m^2.

2.3. *Reactor operation – Phase 2*

The operating conditions identified in Phase 1 were used in Phase 2 to evaluate the performances of the MABR in the removal of organic substances (COD) and total nitrogen (TN) from samples of wastewater collected at the SMAT Castiglione Torinese WWTP.

In Phase 2 the MABR worked in a continuous mode and the wastewater was fed and discharged continuously. According to the results of Phase 1 (see Section 3.1), the process airflow rate was fixed at 0.078 NL/h. The volumetric flow rate of the wastewater was set at 8.00 L/d and increased to 9.67 L/d after 20 days from the beginning of the experimentation, thus decreasing the HRT from 9.0 to 7.4 h. Those HRTs were coherent with values used in recent experiences involving pure or hybrid MABRs (Corsino and Torregrossa, 2022; Telles-Silveira et al., 2022; Uri-Carreño et al., 2021).

The test had a whole duration of 40 days, and, during that period, five different samples of wastewater were fed to the reactor. The composition of the five samples is reported in Table 2. The average composition of the wastewater, analyzed according to the methods described in Section 2.4, was: tCOD, 214 ± 20 mg/L; sCOD, 78.6 ± 11.9 mg/L; TSS, 157 ± 27 mg/L; VSS, 93.9 ± 14.6 mg/L; NH_4-N, 34.1 ± 6.1 mg/L; NO_3-N, 0.22 ± 0.14 mg/L; NO_2-N, 0.11 ± 0.26 mg/L.

2.4. *Analytical methods*

Liquid samples were collected every day, from Monday to Friday, from a 10-L tank, which was stored in a chest fridge at the temperature of 5 °C. The MABR, when was fed continuously, had a spillway useful for keeping the liquid volume constant. The excess liquid was conveyed to the 10-L tank from the spillway via a pipe, by gravity.

The influent and effluent liquid samples were analyzed for chemical oxygen demand (COD), ammonium (NH_4^+-N), nitrite (NO_2^--N), nitrate (NO_3^--N) nitrogen, total (TSS) and volatile suspended solids (VSS). TSS and VSS were determined following standard methods (APHA, AWWA, WEF, 2012). Total and soluble chemical oxygen demand (tCOD and

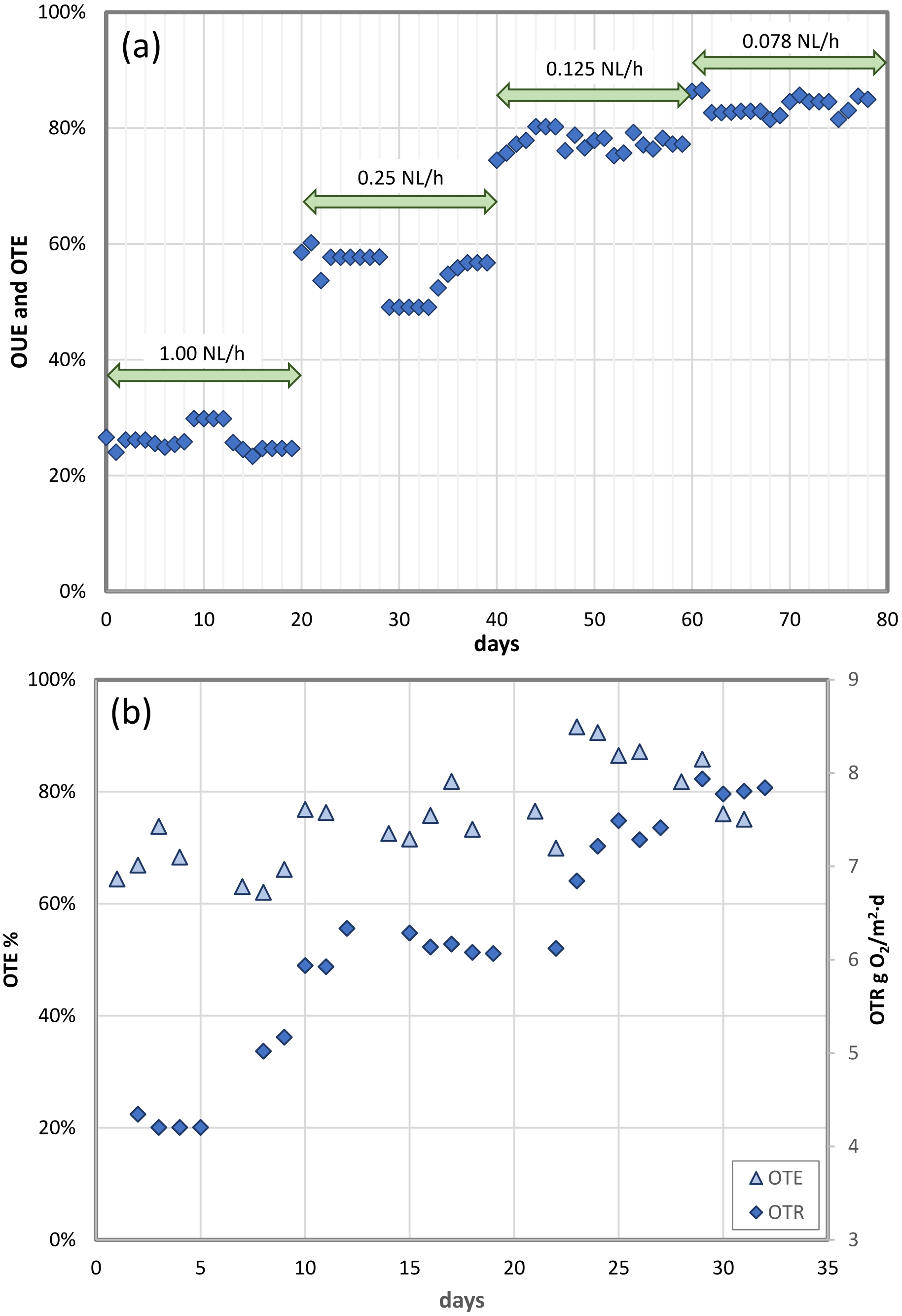

Fig. 2. Values of OTE recorded in Phase 1 (a) and OTE and OTR in Phase 2 (b).

sCOD) were measured using Lovibond kits (COD Vario tube test with three concentration ranges 0–150 mg/L, 0–1500 mg/L and 0–15,000 mg/L) following the manufacturer's instructions of sample digestion using Lovibond digester and Lovibond COD Vario MD 200 spectrophotometer. NO_2^--N and NO_3^--N were analyzed using a Metrohm ECO IC ion chromatograph fitted with a guard column (Metrosep A Supp 17 guard/4.0) and an analytical column (Metrosep A Supp 17–250 mm length, 4 mm diameter). Spectroquant ammonium test 0.010–3.00 mg/L Merck kits were used for estimating NH_4^+-N concentration as per the manufacuturer's instruction using an UV-31 Scan Onda spectrophotometer. All samples measuring the soluble concentrations were filtered using 0.45 μm filters prior to analysis.

2.5. *Techno-economic assessment*

The results obtained in Phases 1 and 2 (see Section 3.1 and 3.2), that is the OTE and OTR values, were used to carry out an assessment of the economic viability of the MABR process. Two scenarios were considered, in which either a conventional aeration process through fine-bubble diffusers or MABR cassettes were used for the revamping of the biological section of a WWTP with a treatment capacity of 25,000 e.i. The comparison, from an economic point of view, was carried out by using the DCF method. The method is based on three variables, namely (i) opportunity cost of capital (i), (ii) lifetime of the project (n) and (iii) cash inflows (It) and outflows (Ot) (Ferella et al., 2019), as shown in Equation (5).

$$NPV = \sum_{t=0}^{n} \frac{(I_t - O_t)}{(1+i)^t} \tag{5}$$

The i parameter measures the return coming from an alternative similar project that has the same risk level. It was fixed equal to 6% and used to actualize the cash outflows over the lifetime of the project. The lifetime is a function of the nature of the project. In this work, the DCF method was employed to find the maximum value of the initial investment for the MABR which could compensate the higher cash outflows, due to the higher energy requirements, of the CAS plant with a return time of 5 years. No cash inflows are expected for this kind of project.

To carry out the comparison between the two plants, it was assumed that the specific amount of wastewater entering the biological section of the WWTP was 0.2 m^3/e.i.•d and it had an average composition of 220 g bCOD/m^3 and 35 g NH_4-N/m^3, that is the average concentrations found in the real wastewater samples used for Phase 2 (see Section 2.3).

For the calculation of the oxygen demand (OD), it was assumed that oxygen was consumed in the processes of bCOD and nitrogen oxidation. It was also precautionary assumed that denitrification did not take place in any system, CAS or MABR (that is all the biodegradable organic substance not involved in anabolic processes was oxidized with free oxygen). The OD for the bCOD oxidation was calculated, as in Equation (6), by considering that the bacteria yield was 0.5 g COD biomass/g bCOD substrate

$$\text{OD for bCOD oxidation} = 25,000 \text{ e.i.} \bullet 0.2 \text{ m}^3/\text{e.i.} \bullet \text{d} \bullet 220 \text{ g bCOD}/\text{m}^3 \bullet (1 - 0.5 \text{ g COD biomass } / \text{ g bCOD}) \tag{6}$$

The OD for nitrogen oxidation (nitrification) was calculated, as in Equation (7), by considering that 20% of the nitrogen present in the wastewater was used for biomass growth.

$$\text{OD for NH}_4^+ - \text{N oxidation} = 4.33 \bullet 0.8 \bullet 25,000 \text{ e.i.} \bullet 0.2 \text{ m}^3/\text{e.i.} \bullet \text{d} \bullet 35 \text{ g bCOD}/\text{m}^3 \tag{7}$$

The OTE was fixed equal to 85% (from the results of Phases 1 and 2) and 15% for MABR and CAS, respectively. Energy calculations were carried out with reference to dry air, with an oxygen content of 23% by weight (w/w).

The initial investment or capital expenditure (CAPEX) included the costs of the blower(s) and diffusers for the CAS plant, and of the blower (s) and MABR cassettes for the MABR plant. The cost of the blower(s) was calculated for both plants by assuming a unit cost of 800 €/kW, taken from the current market. The power requirement of each blower (Pw, kW) was calculated as in Equation (8)

$$P_w = \frac{W \bullet R \bullet T_1}{28.97 \bullet n \bullet e}\left[\left(\frac{p_2}{p_1}\right)^n - 1\right] \tag{8}$$

where: W, weight of the airflow rate, kg/s; R, universal gas constant for air, 8.314 J/mol•K; T1, absolute inlet temperature, K (283 K); p1, absolute inlet pressure, atm (1 atm); p2, absolute outlet pressure, atm (1.45 atm); n = (k-1)/k, where k is the specific heat ratio. For single-stage centrifugal blower power calculations a value of 1.395 is used for k (n = 0.283); 28.97, molecular weight of dry air; e, efficiency, it was assumed equal to 0.75.

The cost of the diffusers for the CAS plant was taken from current market prices and fixed equal to 40 €/unit, as an average value from those found at the principal equipment's providers (SSI Aeration, Sulzer, Evoqua Water Technologies among others). The same reference indicated that the maximum airflow rate which could be elaborated by the diffusers was of 1.74 Nm^3/h. For the calculation of the number of diffusers it was considered that diffusers worked at an average of 70% of the maximum flow rate.

The operational expenditure (OPEX) included labor and maintenance, which were comprehensively estimated at 7% of the CAPEX, and the electric energy cost to supply air through the blower(s). The price of the electric energy for industrial purposes was fixed at 0.16 €/kWh, according to the indication of the Italian Regulatory Authority for Energy, Networks and Environment (ARERA, 2024).

In the end, a sensitivity analysis was carried to assess the relative importance of the input parameters on the maximum value allowable for the MABR initial investment with a return time of 5 years. The unit cost of a blower, the cost of diffusers and electric energy, and the opportunity cost of capital were the factors selected for the analysis. A tornado chart was used to represent the effect of a variation of ±50% in each parameter (as in Sillero et al., 2023), to understand the effect of each of them on the maximum allowable MABR initial investment.

3. Results and discussions

3.1. *Optimization of the oxygen utilization efficiency (OUE)*

The aim of Phase 1 was finding the working conditions which maximized the utilization of the oxygen supplied to the MABR. Fig. 2a shows the values of the OUE calculated as in Equation (2). The concentration of DO into the bulk liquid was found close to zero for all the duration of the test. Consequently, the difference in the oxygen mass flow rate between the inlet and the outlet of the reactor (OTE) was equal to the amount of oxygen consumed by the biofilm (OUE).

As reported in Table 3, in the first period the process airflow was originally set at 1 NL/h at the outlet of the reactor, and it was consequently recorded at the inlet, where it was measured an average value of 1.15 NL/h (see Table 3). In the same period, the average oxygen concentration in the outlet airflow was measured at 17.8 ± 0.5%, the OTE was calculated equal to 25.7 ± 2.1%. Such OTE value was deemed to be too low for using MABR at the best of its potentiality. Consequently, in the three subsequent periods the process airflow rate at the outlet of the reactor was lowered to 0.250, 0.125 and finally to 0.078 NL/h. The corresponding concentrations of oxygen in the outlet airflow and the calculated OTE and OTR values are reported in Table 3.

The increasing relative difference between the inlet and outlet airflow and the decreasing concentration of oxygen in the outflow determined rising OTE values, which reached a maximum value of approx. 84% at the end of the fourth period. In the experiences reported in the literature the process air was usually set upstream the reactor (see, for example, Ravishankar et al., 2022) and measured downstream. With that working modality it is very difficult or definitely not possible obtaining high values of OTE. Conversely, in this experience, the imposition of decreasing airflow values at the outlet of the reactor allowed to observe OTEs of more than 80%, of the same order of those obtainable with a dead-end operating mode, but without the drawbacks related to such an operating condition (He et al., 2021). As it will be shown in Section 3.3, the OTE value reached by the system had a strong impact on the economic sustainability of the process. Decreasing OTR

Table 3
MABR outlet and inlet airflow rate, concentration of oxygen in the outlet airflow, calculated values of OTE and OTR (average value ± standard deviation).

Period	Outlet air flow rate (NL/h)	Inlet air flow rate (NL/h)	outlet air O_2 (%)	OTE (%)	OTR (g O_2/m^2·d)
1	1.000	1.149 ± 0.005	17.8 ± 0.5	25.7 ± 2.1	8.15 ± 0.30
2	0.250	0.385 ± 0.007	14.6 ± 1.1	54.6 ± 3.8	5.99 ± 0.50
3	0.125	0.248 ± 0.010	9.34 ± 0.82	77.5 ± 1.8	5.51 ± 0.25
4	0.078	0.206 ± 0.017	9.39 ± 0.63	83.7 ± 1.6	5.10 ± 0.49

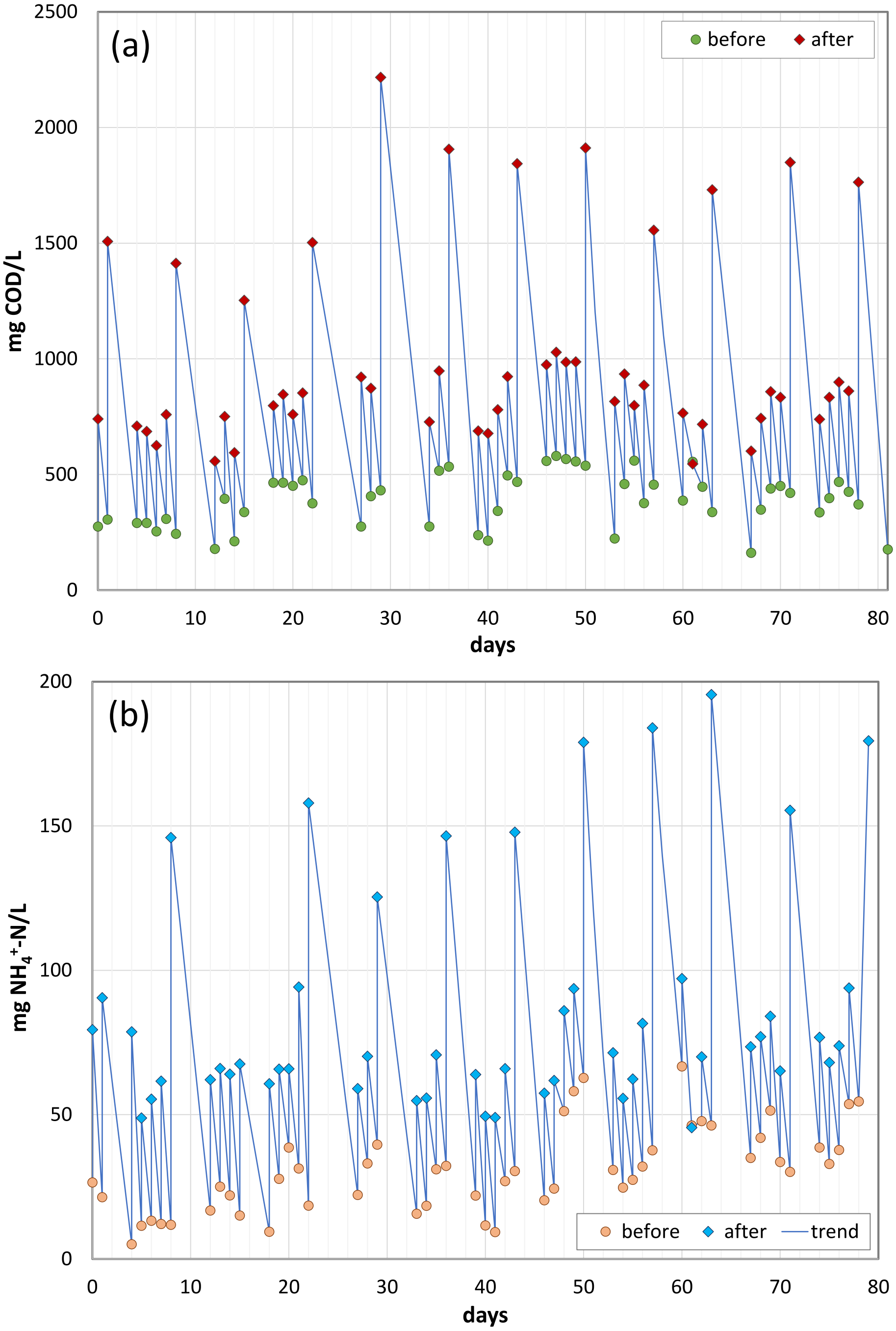

Fig. 3. Trend of COD (a) and NH_4^+-N (b) in the MABR, from one feeding to the subsequent feeding.

values, from approx. 8 to 5 g O_2/m^2•d, were recorded from the first to the fourth period of the experimentation.

The operations carried out in Phase 1 were not aimed at the optimization of the removal of the organic substance and nitrogen fed to the reactor with the synthetic solution. The two substrates (COD and NH_4^+-N) were provided with the purpose of supporting the biological processes taking place in the MABR, that is the growth of heterotrophic and autotrophic biomass to produce a steady biofilm. Fig. 3a and b shows the trend of COD and NH_4^+-N in the reactor, from one feeding to the subsequent feeding, given that the MABR was working in a fed-batch mode. In Fig. 3, the dots which are named “before” represent the concentration of COD or NH_4^+-N immediately before the feeding, which took place once a day. The dots which are named “after” represent the concentration of COD and NH_4^+-N after the volume of synthetic wastewater was mixed with the liquid phase remaining in the MABR. This operation determined a sudden increase in the COD and NH_4^+-N in the reactor. The biological processes occurring in the MABR determined a reduction in the concentration in the subsequent 24 h. Fig. 3a and b shows that the average removal efficiency of the COD was very variable, with an average of 55% and values close to 90% at the beginning of each new week. A similar trend, with higher fluctuations, can be seen also for NH_4^+-N, where the average removal value was of approx. 60%. Concentration of NO_2^--N and NO_3^--N remained, on average, at low values, thus demonstrating a good capacity of the system in denitrification (data not shown). The efficiency removal of both COD and NH_4^{+-}N did not seem to be affected by the airflow values and by the OTEs achieved in the reactor.

Table 4
Organic (tCOD) and ammonium nitrogen (NH_4^+-N) loading rate which resulted from the characteristics of the wastewater samples (average value ± standard deviation).

	g/d	g/L•d	g/m^2•d
tCOD – HRT 9.0 h	1.64 ± 0.09	0.55 ± 0.03	6.58 ± 0.36
tCOD – HRT 7.4 h	2.09 ± 0.23	0.70 ± 0.08	8.38 ± 0.94
NH_4^+-N – HRT 9.0 h	0.23 ± 0.01	0.08 ± 0.00	0.93 ± 0.03
NH_4^+-N – HRT 7.4 h	0.37 ± 0.06	0.12 ± 0.02	1.46 ± 0.24

3.2. COD and N removal from a real wastewater

The purpose of Phase 2 was confirming the removal capacity of the MABR, functioning at the operating conditions defined in Phase 1, against the organic substance and nitrogen present in the real wastewater samples coming from a full-scale WWTP. Since the quality of the wastewater was almost constant over the whole testing period, a change in the HRT was done in order to increase the load of substrate available for the biofilm and, consequently, to test the removal capacity of the system under an increasing load. The values of organic (tCOD) and ammonium nitrogen (NH_4^+-N) loading rate, which resulted from the characteristics of the wastewater samples, were calculated for the two periods with reference to the working volume of the reactor (3 L) and the surface of the membrane (0.25 m^2), and are shown in Table 4.

In Phase 2 both the OUE (and OTE) and the removal of the organic substance and nitrogen in all its forms were monitored. The concentration of oxygen in the outlet airflow was recorded at a quite constant value (17.5% ± 0.8%) for the whole duration of the test, while the

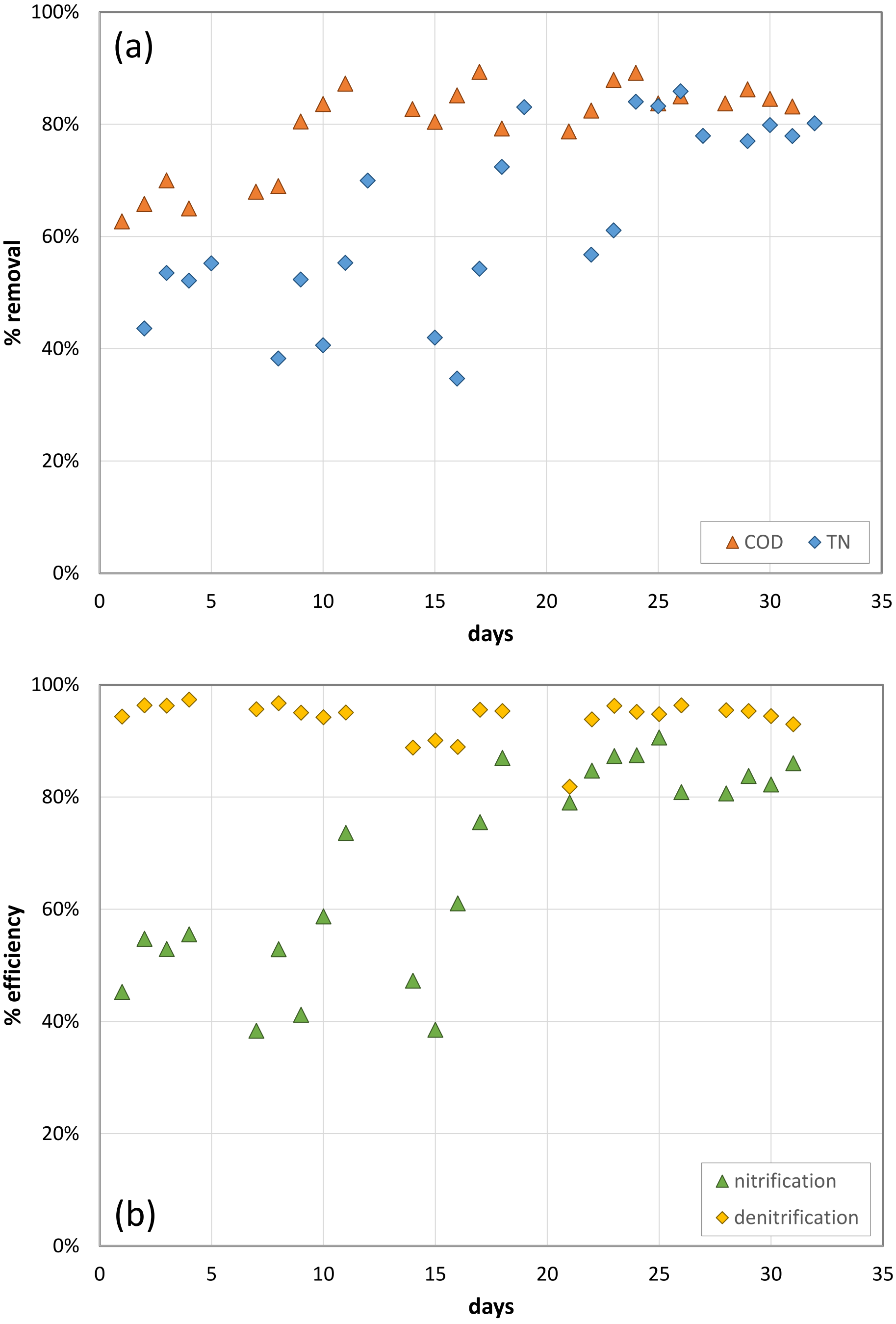

Fig. 4. Efficiency of COD and TN removal (a) and nitrification – denitrification (b).

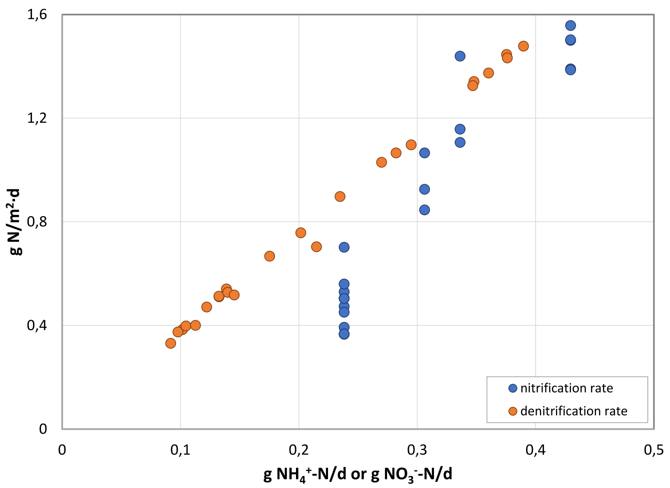

Fig. 5. Specific nitrification and denitrification rate (g $N/m^2·d$) as a function of the nitrogen load (g NH_4^+-N/d or g NO_3^--N/d).

Table 5
Air for the oxidation processes, blower power, required energy and cost items necessary for the revamping of the biological section of the WWTP with the two types of plants (CAS and MABR).

	CAS	MABR
O_2 to be supplied (kg/d)	15,416	2720
Air to be supplied (kg/d)	67,026	11,828
Air to be supplied (kg/s)	0.78	0.14
Blower power (kW)	33	6
Required energy (kWh/d)	792	144
Cost item (k€)		
Diffusers	70.9	–
MABR cassettes	–	235 (*)
Blower (x2)	52.8	9.6
Labor and maintenance	8.7	17.1 (*)
Energy	46.3	8.4

(*) after the application of the DFC method, payback time = 5 years.

concentration in the bulk liquid was close to zero. As in Phase 1, that occurrence determined a substantial correspondence between the values of OUE and OTE. The OTE values calculated in Phase 2 increased from 70% in the first days of the test to approx. 82% at the end of the test (see Fig. 2b), with an average value of 76.5% ± 3.9%. The OTE recorded in the last 10 days of Phase 2 was very similar to that obtained in the last period of Phase 1. The consequent OTR was of 6.21 ± 1.16 g O_2/m^2•d, with a maximum value of approx. 8 g O_2/m^2•d in the last week of the test.

The efficiency in COD removal reached values in the order of 85%, starting from day 15th from the beginning of the test, as shown in Fig. 4a. Maximum removal rates of 690 $g/m^3·d$ and 8.3 $g/m^2·d$ were observed, with average values of 650 $g/m^3·d$ and 7.8 $g/m^2·d$ in the last 10 days of the test (data not shown). The values of COD removal reported above were in line with those found by Ravishankar et al. (2022), in a test which made use of a pure standalone MABR system fed with a primary treated wastewater. Experiences of a such type, that is involving a pure MABR fed with real wastewater are however not so frequent in the literature.

A maximum efficiency in TN removal of 86% was reached after 30 days from the beginning of the test (Fig. 4a). An average value of 80% was maintained in the last period of the experimentation. This result made the system quite promising also for TN removal, demonstrated by a good capacity in both nitrification and denitrification. In fact, as shown in Fig. 4b, the efficiency of nitrification increased from values in the order of 50%, in the first ten days of the tests, to 85%, in the last ten days, with maximum values of NH_4^+-N removal efficiency of around 90%. The increase in the nitrification efficiency observed during the execution of the test was probably due to a progressive growth and achievement of steady state of the autotrophic biomass, which required high SRTs (Corsino and Torregrossa, 2022). The observed rising nitrification efficiency seemed to suggest an absence or very low competition between nitrifiers and heterotrophs in the biofilm. However, the lowest NH_4^+-N concentration observed at the outlet of the reactor, in the order of 4 mg/L, was higher than the average concentration values which are obtainable with either more traditional systems (such as CAS) or hybrid MABR (Li et al., 2023a). The mass transfer limitation of NH_4^+-N, due to the biofilm thickness, has a significant role in counter-diffusional attached system, thus keeping the achievement of concentration below 1 mg/L a challenge in pure MABRs (Ravishankar et al., 2022).

Conversely, the efficiency of denitrification was at very high values (average 94%) since the very first days of the test (see Fig. 4b). In all the biological processes which make use of heterotrophic denitrification for nitrogen removal, COD/N ratio and oxygen utilization were demonstrated to be key parameters. Previous works that have studied the effect of COD/N ratio on TN removal found that denitrification could be realized in an efficient way in the presence of COD/N values from 5 to 15 (Lin et al., 2015; Li and Zhang, 2018). However, values in the lower part of the range (5–8) could be critical when the COD present in the wastewater has a poor biodegradability or is not completely available for the biomass (Mehrabi et al., 2022). In this study the COD/N ratio decreased from 7.1, when the HRT was 9.0 h, to 5.7, when the HRT was 7.4 h, as it can be calculated from the data of Table 4, because of the variable characteristics of the fed wastewater. Notwithstanding the observed decrease, the COD/N ratio remained in the field recommended for optimal denitrification (Xiao et al., 2021). Counter diffusional biofilm systems, such as MABRs, require an accurate balance between the OD and oxygen supply, to avoid that the biofilm can turn completely aerobic, thus preferring the utilization of oxygen instead of nitrate (Landes et al., 2021). In this study the oxygen dissolved in the bulk liquid was maintained at values close to zero, thus guaranteeing optimal conditions for an efficient denitrification. Maximum specific removal rates of 1.5 $g/m^2·d$ were found for both nitrification and denitrification. Average values equal to 1.38 and 1.32 $g/m^2·d$ were observed in the last ten days for nitrification and denitrification, respectively, which were in line with the values obtained in a pure MABR fed with real wastewater (Ravishankar et al., 2022). However, the trend of the specific removal rates for nitrification and denitrification (see Fig. 5), as a function of the available nitrogen load (in the form of NH_4^+-N or NO_3^--N, respectively), suggested that the capacity of the system in TN removal could be further increased, by increasing the incoming load of NH_4^+-N. That should have a positive effect on the utilization of the membrane, thus allowing increasing the OTR and decreasing the number of cassettes necessary for the treatment of a unit wastewater flow.

3.3. Techno-economic assessment

The techno-economic assessment was carried out to compare the viability of using MABR cassettes, instead of a conventional aeration process via fine-bubble diffusers, to renovate the biological section of a WWTP with a treatment capacity of 25,000 e.i. Under the hypotheses detailed in Section 2.5, the OD of the processes of carbon oxidation and nitrification resulted of 550 kg/d and 606 kg/d, respectively, for a total of 1156 kg O_2/d. As stated in Section 2.5 it was precautionary assumed that all the organic substance not involved in anabolic processes was oxidized with free oxygen (i.e. absence of denitrification). However, because of the quite low organic load found in the wastewater used for the test, the characteristics of which are listed in Table 2, a safety factor of 2 was considered for the calculations of the energy demand of the plant. The amount of oxygen to be supplied to the plant, the consequent amount of air, the power of the blower to be used in the two cases (CAS and MABR) and the required energy are detailed in Table 5.

Because of the lower OTE of the CAS reactor, the amount of air to be supplied was 5.7 times more than that of the MABR system. The

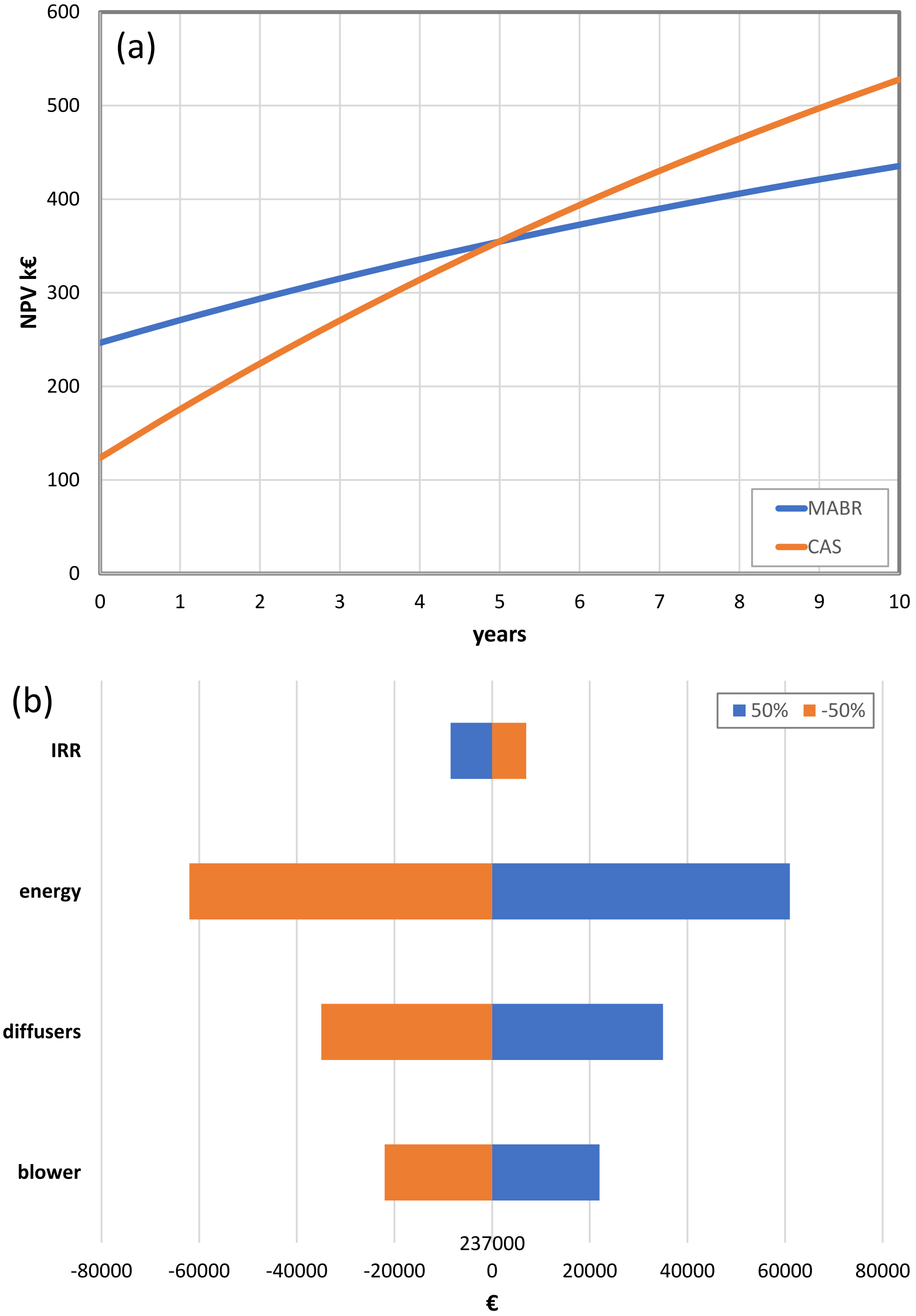

Fig. 6. Cash flow for a CAS and a MABR plant (a) Tornado chart for the sensitivity analysis of the initial investment for the MABR cassettes (b).

supplement of approx. $67 \bullet 10^3$ kg air/d (corresponding to $51.8 \bullet 10^3$ Nm^3/d) required 1773 diffusers working at an average of 70% of the maximum flow rate.

Table 5 also details the cost items necessary for the revamping of the biological section of the WWTP.

The CAS CAPEX resulted of 123.7 k€, including the cost of a spare blower, which was also considered for the MABR plant. The annual OPEX of the CAS plant was calculated equal to 55.0 k€, 84% of that for energy and the remaining amount for labor and maintenance. Because of the better use of oxygen, the annual energy cost of the MABR plant was estimated to only 8.4 k€, approx. 5.5 times less than that of the CAS plant.

Based on the OTR value of approx. 0.008 kg $O_2/m^2 \bullet d$, calculated from the results shown in Section 3.2, the membrane surface necessary for the wastewater treatment was of 340,000 m^2. Given that each cassette has 48 modules, with 40 m^2 of membrane each, a total of 177 cassettes were deemed to be necessary for the biological section of the plant. As shown in Fig. 6a, which reports the cash flow for the two plants, a MABR plant could become a profitable investment, on a return time of 5 years, if the cost of the MABR cassettes was inferior to 237 k€, that is approx. 1340 € for each cassette. In that case, the savings in the energy cost due to the better utilization of oxygen could compensate the higher investment necessary for the MABR plant. It is evident that an increase in the OTR could reduce the number of cassettes necessary for the treatment and, consequently, the initial investment. The operating conditions fixed in Section 3.2, that is the control of the airflow rate downstream the membrane, allowed to obtain very high values of OTE, but the OTRs remained at quite low values. However, the increase in the OLR observed in the last period of the test (Fig. 2b) and the trend in the specific TN removal, shown in Fig. 5, suggest that the achievement of higher oxidation efficiency per unit area of membrane is possible.

The results of the sensitivity analysis are shown in the tornado chart reported in Fig. 6b. Among the analyzed parameters (namely the unit cost of a blower, the cost of diffusers, the cost of energy and the opportunity cost of capital), the cost of energy had the greatest impact on the economic sustainability of the project, in agreement with other studies where this kind of analysis was carried out (Sillero et al., 2023). An increase of 50% in the price of energy, that is from 0.16 to 0.24 €/kWh, would make profitable a MABR plant with an initial cost of approx. 300 k€, that is 26% more than that calculated in the base scenario (cost of energy of 0.16 €/kWh). An increase (or decrease) of 50% in the cost of diffusers or in the cost for unit power of the blower would affect the initial cost of the MABR cassettes by 15% or 9% respectively. A variation of the IRR in the range 3–9% affected the cost of MABR cassettes by only approx. 3%.

4. Conclusions

The implementation of the MABR technology at a WWTP can improve the use of energy for oxidation processes, thus helping the achievement of the climate neutrality goal. In this study, the feasibility of using MABR cassettes instead of traditional fine-bubble diffusers for the aeration process, to renovate the biological section, was assessed for a WWTP with a treatment capacity of 25,000 e.i. The data used in the assessment came from tests carried out in a pure, open-end MABR working under optimized working conditions with real wastewater samples. The results obtained in this study demonstrated that.

- The control of the flow at the outlet of the MABR was used as a strategy to obtain high OTE values. Specifically, this resource allowed to achieve OTEs of more than 80%, of the same order of those obtainable with a close-end configuration and not so frequent in the available literature.
- Removal efficiencies of COD and TN of approx. 85% were achieved for both substances in samples of real wastewater. The oxygen for the biological processes was utilized in a very efficient way, leaving concentration of DO in the bulk liquid close to zero. Because of the very good oxygen utilization, denitrification showed very high efficiencies (approx. 95%) for all the duration of the test.
- The techno-economic analysis made to compare a MABR plant with a traditional CAS with the same treatment capacity, that is 25,000 e.i., revealed that the energy required by the MABR was only approx. 1/5 of that necessary for the CAS.
- Under a fixed return time of 5 years, a MABR plant could become a profitable investment, compared to a traditional CAS with a CAPEX of 123.7 k€, if the cost of the cassettes was inferior to 237 k€. The results of a sensitivity analysis imposing a variation of ±50% on the input parameters (cost of blower, diffusers, electric energy, and opportunity cost of capital) showed that the cost of electric energy had the highest impact on the maximum allowable value of the MABR investment, which was affected by ± 26% with respect to the value calculated in the reference scenario.
- However, the relationship between the specific removal rates for nitrification and denitrification and the incoming nitrogen load revealed the presence of a residual capacity of the system for TN removal. That would allow working with high OTR values and consequently increase the profitability of the MABR system.

CRediT authorship contribution statement

Giuseppe Campo: Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Alberto Cerutti:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Conceptualization. **Mariachiara Zanetti:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Barbara Ruffino:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giuseppe Campo, Alberto Cerutti, Mariachiara Zanetti, Barbara Ruffino reports financial support was provided by SMAT, Metropolitan Water Company of Turin. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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