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Membrane bioreactor operated under intermittent aeration a comprehensive comparison with an IFAS-MBR: A pilot plant experience

Antonio Mineo, Paulo Marcelo Bosco Mofatto, Alida Cosenza, Daniele Di Trapani *, Giorgio Mannina

Engineering Department, Palermo University, Viale delle Scienze ed. 8, Palermo 90128, Italy

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ABSTRACT

This study presents a comparison of two advanced wastewater treatment technologies operating under intermittent aeration (IA): the Membrane Bioreactor (MBR) (Period I) and the Integrated Fixed Film Activated Sludge (IFAS)-MBR (Period II). Both technologies were applied to a pilot plant at the Water Resource Recovery of Palermo University and operated to remove carbon and nutrients from real wastewater. The ultimate goal was to provide a comprehensive comparison in terms of: carbon, nitrogen and phosphorus removal, nitrous oxide (N_2O) emissions, membrane fouling, and carbon footprint. Results showed a better performance in nitrogen processes for IFAS-MBR during Period II. Total nitrogen removal efficiencies were 76 % and 83 % for Period I and II, respectively. The total N_2O emissions were 1.7 % and 0.38 % for Period I and II, respectively. Conversely, the carbon footprint increased during Period II due to a higher membrane fouling rate and sewage sludge production of 2.5 and 2.8 $kgCO_{2,eq}$ m^{-3} for Period I and II, respectively. The experiments confirmed the beneficial role played by the biofilm in terms of the reduction/mitigation of N_2O emissions.

1. Introduction

The Membrane Bioreactor (MBR) is an established technology that can improve biological nutrient removal and reduce the excess sludge production in wastewater treatment plants (WWTPs) [19]. The MBRs have several advantages compared to conventional activated sludge (CAS) systems especially in terms of providing higher effluent quality, and of strongly reducing pathogenic bacteria [2,16]. This aspect is particularly notable, as MBRs also ensure water production for reuse, especially in the agricultural sector for irrigation purposes [7,24]. However, membrane fouling and higher energy consumption than CAS represent two significant drawbacks of MBR application [32].

Several strategies can be applied to lower the energy requirement and waste sludge production, ultimately reducing the carbon footprint (CF) [22].

One solution might be to adopt an intermittent aeration (IA) operation strategy to reduce the energy used for reactor aeration. Furthermore, the IA strategy allows for the removal of carbon and nitrogen in a unique reactor. Very recently, Yilmaz et al. [34] demonstrated that intermittent aeration applied to an MBR led to high performance (high nitrogen removal and reduced sewage sludge production) with the advantages of reducing the energy demand than continuous aeration. However, the influence of IA on energy demand and sewage sludge production in the context of CF reduction remains unexplored. Moreover, the performance of MBR systems can also be improved by the addition of an integrated fixed film activated sludge (IFAS) process coupled to MBR, thereby realising an IFAS membrane bioreactor (IFAS-MBR) process [20,21]. Although the integration of Integrated Fixed-film Activated Sludge (IFAS) and Membrane Bioreactor (MBR) technologies has been previously investigated, particularly in relation to excess sludge reduction, enhanced denitrification performance, and mitigation of membrane fouling [17,26], limited information is available regarding the performance of IFAS-MBR systems under intermittent aeration (IA). Specifically, there is a lack of studies addressing the carbon footprint, N_2O emissions, biokinetic parameters and energy demand under such operational regimes

In this light, the manuscript aims to compare two IA systems (MBR-IA and Integrated Fixed-film Activated Sludge - IFAS-MBR-IA) in terms of carbon and nitrogen removal, nitrous oxide emissions, waste sludge production, energy demand and CF. The present study entails innovative advances in the current state of knowledge by systematically comparing two IA-configured systems: MBR-IA and MBR-IFAS-IA with particular

* Corresponding author.
E-mail address: daniele.ditrapani@unipa.it (D. Di Trapani).

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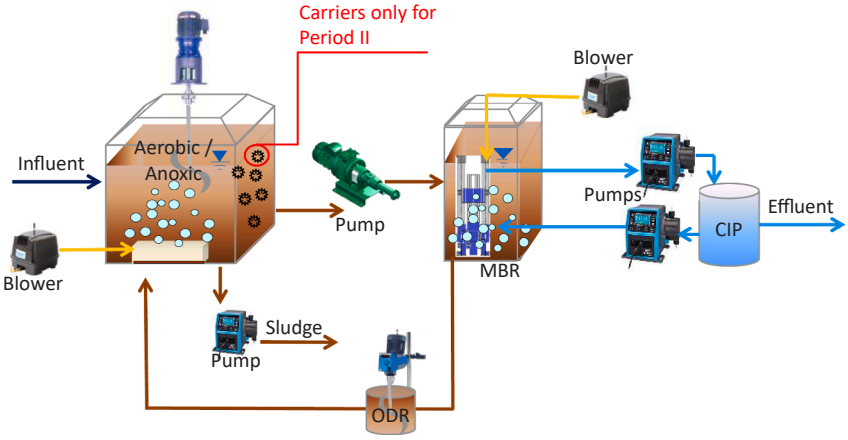

Fig. 1. Pilot plant layout.

emphasis on differentiating the contributions of attached and suspended biomass. The innovative aspect of this work lies in the integrated evaluation of both biomass fractions through detailed respirometric analyses, which enables a kinetic characterisation of substrate uptake and nitrogen transformation pathways. Furthermore, the study assesses the relative impact of each biomass type on GHG emissions and CF, providing novel insights into the environmental performance of hybrid systems under IA.

2. Material and methods

2.1. Pilot plant description

A pilot plant was set-up and monitored at the Wastewater Resource Recovery Facility (WRRF) of Palermo University. The pilot plant was characterised by: one intermittent aeration reactor (IA) operating for 40 min under aerobic conditions and 20 min under anoxic conditions, followed by an MBR with an ultrafiltration hollow fibre membrane module (Puron® 3 bundle, pore size 0.03 μm, membrane surface area 1.4 m^2). The aeration rate through the membrane module was set at 20 LPM, corresponding to aeration amount per unit membrane area per unit time of 14.3 L m^{-2} min^{-1}. During Period II, carriers were inserted inside the IA reactor (0.95 g/cm^3 density and 500 m^2/m^3 specific surface – Amitec Co. Ltd).

2.2. Experimental period and wastewater features

The experimental activity had an overall duration of 70 days during which the pilot plant was operated according to two configurations: i. MBR-IA - Period I; ii. IFAS-MBR-IA - Period II. During the two experimental periods, the two configurations were compared in terms of pollutant removal, membrane fouling, sewage sludge production, greenhouse gas production, and carbon footprint. The pilot plant was fed with real wastewater collected from the University Campus [23], which was naturally exhibited fluctuations in its quality features. Nevertheless, the soluble COD, ammonium nitrogen and F/M ratio were quite similar in the two periods, thus enabling a quit reliable comparison between the two configurations that were operated in-series during the experimental campaign.

2.3. Analytical methods

The chemical parameters mentioned above (COD, NH_4-N, PO_4-P, BOD, TN, TSS) and nitrate (NO_3^+-N), nitrite (NO_2^+-N) were measured twice a week according to Standard Methods [1]. Respirometric tests and sludge volume index (SVI) were evaluated in the intermittent aeration reactor to analyze the kinetic parameters [10] and the sludge settling performance, respectively.

Moreover, soluble microbial products (SMP) and extracellular polymeric substances (EPS) were analyzed according to the methods described by Mannina et al. [19]. Both analyses were carried out in terms of carbohydrates and proteins, and samples were collected once a week in the intermittent aeration and MBR tanks.

The observed yield coefficient (Y_{obs}) was calculated according to de Oliveira et al. [8] (Eq.1).

$$Y_{obs} = \frac{\Delta X}{Q_i \bullet (TCOD_{in} - TCOD_{out})} \quad (gSSTgCOD^{-1}) \tag{1}$$

where $TCOD_{in}$ and $TCOD_{out}$ are the Total COD concentrations in the influent and effluent, respectively, Q_i is the daily influent flow rate, and ΔX is the daily excess sludge production.

N_2O concentrations (both dissolved and gaseous) were sampled and measured according to the methods described by Mannina et al. [18] by using a Gas Chromatograph (GC) (Thermo Scientific™ TRACE GC) equipped with an Electron Capture Detector (ECD). Furthermore, the N_2O-N fluxes were determined based on the off-gas flow rate measurements in the intermittent aeration and MBR tanks.

The emission factor (EF_{N2O}) was evaluated as suggested by Tsuneda et al. [29].

Regarding membrane fouling, the total membrane resistance (R_T) was calculated every day according to Eq. 2.

$$R_T = \frac{\Delta P}{\mu \bullet J} \quad (m^{-1}) \tag{2}$$

where ΔP [kPa] represents the transmembrane pressure (TMP), J (m^3 m^{-2} s^{-1}) and μ [Pa.s] are the permeate flux and viscosity, respectively.

Membrane fouling was controlled according to the manufacturer's suggestion by performing physical and chemical cleanings [4].

2.4. Carbon footprint

During the experimental campaign, direct (DE), indirect (IE), and derived emissions (DerE) were calculated to determine the total plant carbon footprint (CF).

The DEs were calculated according to Boiocchi et al. [3] as the sum of three equivalent CO_2 compounds: i. the amount due to the organic carbon oxidation ($CO_{2,OrgOx}$, Eq. 3), and ii. the amount due to endogenous bacteria metabolism ($CO_{2,Endog.}$, Eq. 5); iii. amount of N_2O emission ($CO_{2eq,N2O}$, Eq. 6).

$$CO_{2,OrgOx} = FC_S * r_{o2} \quad (kgCO_2 \quad d^{-1}) \tag{3}$$

FC_S is the conversion factor representing the CO_2 produced per kg of adopted O_2 (equal to 1.1 kg CO_2 kg^{-1} O_2) and r_{o2} is the amount of

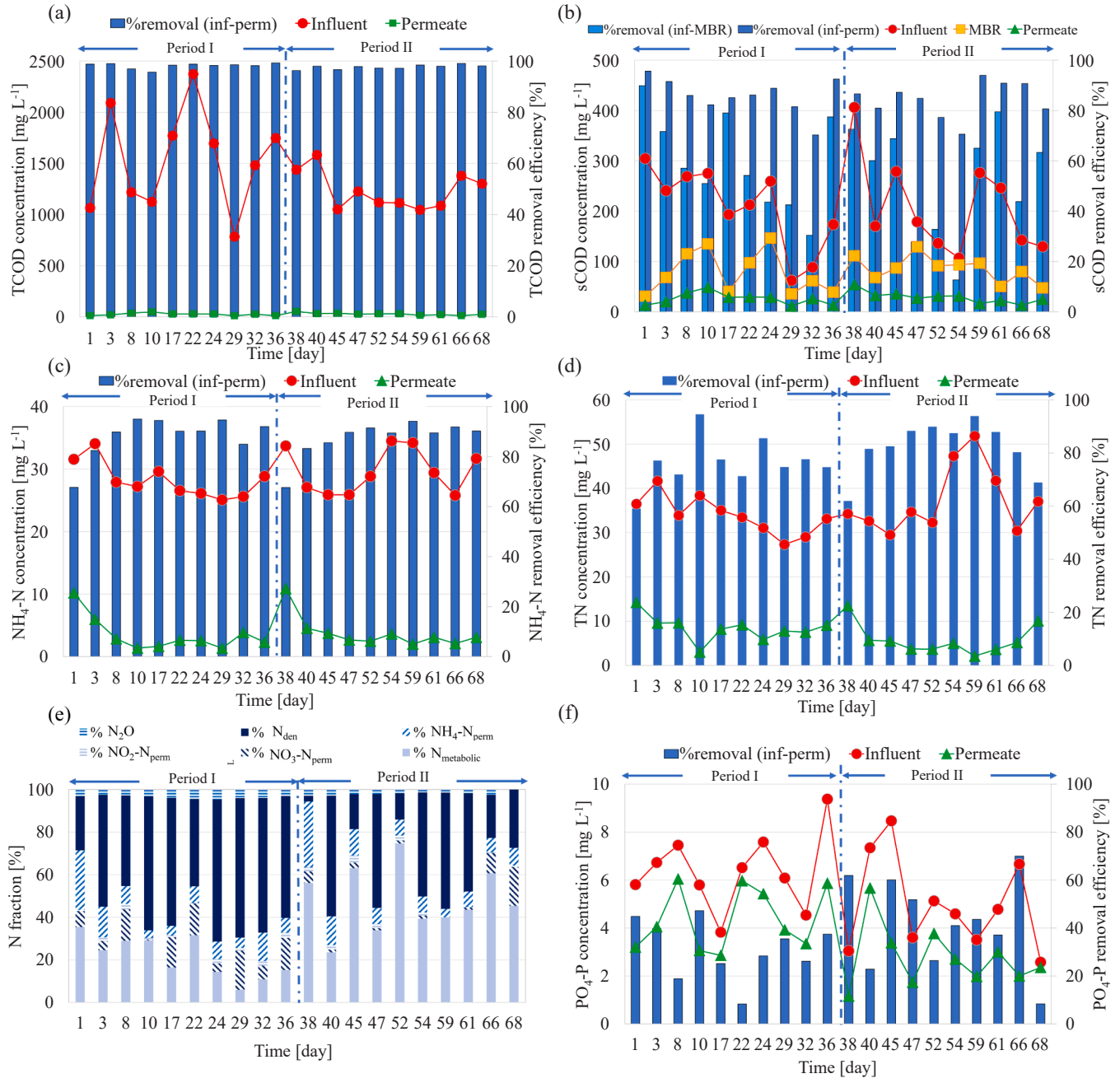

Fig. 2. Trend of influent, effluent, and removal efficiency for total TCOD (a), sCOD (b), NH_4-N (c), TN (d) and nitrogen fractionation (e), and PO_4^{-3}-P (f).

oxygen consumed per day calculated according to Eq. 4:

$$r_{o2} = V_{rs} * \left(\frac{1}{f - 1.42 * Y}\right) \left(kgO_2 d^{-1}\right) \quad (4)$$

where V_{rs} is the BOD_5 removed [in $kgBOD_5\ d^{-1}$] calculated based on the measured data, f is equal to 0.68 and Y is the cell growth rate [in $kgVSS\ kgBOD_5^{-1}$]. The average value of the calculated Y_{obs} values was adopted here.

$$CO_{2,Endog} = FC_{End} * m_{VSS} \quad \left(kgCO_2 d^{-1}\right) \quad (5)$$

The conversion factor FC_{End} represents the CO_2 emitted per kilogram of produced VSS (equal to 1.947 kg CO_2 kg^{-1}VSS), where m_{VSS} is the mass of VSS.

$CO_{2eq,N2O}$, was calculated according to Eq. 6:

$$CO_{2,N2O} = Q_g * C_{g,N2O} * GWP_{N2O} \quad \left(kgCO_{2eq} d^{-1}\right) \quad (6)$$

where Q_g [$m^3\ d^{-1}$] is the average gas flow, $Cg_{,N2O}$ [$kgN_2O\ m^{-3}$] is the measured N_2O concentration in the off-gas and GWP_{N2O} [$kgCO_{2eq}\ kgN_2O^{-1}$] is the N_2O global warming potential (equal to 298 according to [14]).

The IEs were calculated by Eq. 7 summing the equivalent CO_2 related with the energy consumption ($CO_{2eq,En}$) (Eq. 7) and sludge management ($CO_{2eq,Sludge}$) (Eq. 8):

$$CO_{2eq,En} = E_n * FC_{En} \quad \left(kgCO_2 kWh^{-1}\right) \quad (7)$$

where E_n [kWh d^{-1}] is the energy consumed in the water line and FC_{En} [$kgCO_{2eq}\ kWh^{-1}$] is the conversion factor transforming consumed energy into equivalent CO_2 (0.252 $kgCO_{2eq}\ kWh^{-1}$ according to [11]):

Table 1
Influent and operational features for Periods I and II; SD = Standard Deviation.

			Period I		Period II	
Symbol	Description	Unit	Average	SD	Average	SD
TCOD	Total COD	mg/L	1534.4	493.5	1234.0	184.8
sCOD	soluble COD	mg/L	207.8	80.5	207.1	93.4
NH_4-N	Ammonia	mg/L	28.2	2.8	29.7	3.6
PO_4-P	orthophosphate	mg/L	6.4	1.6	5.0	2.0
BOD	Biochemical Oxygen Demand	mg/L	200.5	131.0	454.5	63.5
TN	Total nitrogen	mg/L	40.0	6.1	40.2	4.4
TSS	Total suspended solids	mg/L	732.3	253.6	485.0	182.0
F/M	Food / Microorganism Ratio	[gCOD/ gTSS d]	0.09	0.04	0.07	0.02
Q_{IN}	Flow Rate	[L h^{-1}]	14.2	0.6	16.5	0.5
SRT	Sludge Retention Time	[d]	176.7	49.9	12.6	3
TSS_{IA}	Total suspended solids IA reactor	[g/L]	3.65	0.45	3	0.8
TSS_{MBR}	Total suspended solids MBR	[g/L]	7.09	3.52	5.6	2.8
sAB	Superficial attached biofilm	[g/m^2]	-	-	13.7	3.1
AB	Attached biofilm	[g/L]	-	-	1.2	0.3
AR	Aeration Rate	LPM	20	-	20	-

Table 2
Average observed yield coefficient and SVI for each period.

			Period I	Period II
Symbol	Description	Unit	Value	
Y_{obs}	Observed yield coefficient	[gTSS/gCOD]	0.12	0.2
SVI	Sludge Volume Index	[mL g^{-1}]	88	95

$$CO_{2eq,Sludge} = M_{sludge} * FC_{Sludge} \quad \left(kgCO_{2eq}d^{-1}\right) \tag{8}$$

where M_{sludge} [ton d^{-1}] refers to the daily mass of wasted sludge and FC_{Sludge} [$kgCO_{2eq}$ ton^{-1}] is the emission factor due to the sludge management (714.74 $kgCO_{2eq}$ ton^{-1} according to [35]).

The DerEs were calculated according to Eq. 9:

$$DerE = \quad CO_{2eq,effBOD} + CO_{2eq,effN2O}\left(kgCO_{2eq}d^{-1}\right) \tag{9}$$

where $CO_{2eq,effBOD}$ (Eq. 10) and $CO_{2eq,effN2O}$ (Eq. 11) are due to BOD and dissolved N_2O, respectively, discharged by the pilot plant.

$$CO_{2eq,effBOD} = M_{BOD} * FC_{BOD}\left(kgCO_{2eq}d^{-1}\right) \tag{10}$$

where M_{BOD} [kgBOD d^{-1}] refers to the daily BOD discharged and FC_{BOD} [$kgCO_{2eq}$ $kgBOD^{-1}$] is the related conversion factor (0.96 $kgCO_{2eq}$ $kgBOD^{-1}$ according to [3]).

$$CO_{2eq,effN2O} = Q_w * C_{l,N2O} * GWP_{N2O}\left(kgCO_2d^{-1}\right) \tag{11}$$

where Q_w [m^3 d^{-1}] is the treated wastewater, $C_{l,N2O}$ [kgN_2O m^{-3}] is the dissolved N_2O concentration in the treated effluent and GWP_{N2O} [$kgCO_{2eq}$ kgN_2O^{-1}] is the N_2O global warming potential (298 according to [14]).

3. Results and discussion

3.1. Pilot plant performance

Fig. 2 illustrates the influent and effluent concentration patterns, as well as the removal efficiencies for TCOD, sCOD, NH_4-N, TN and PO_4-P, along with the nitrogen mass balance. In terms of carbon removal,

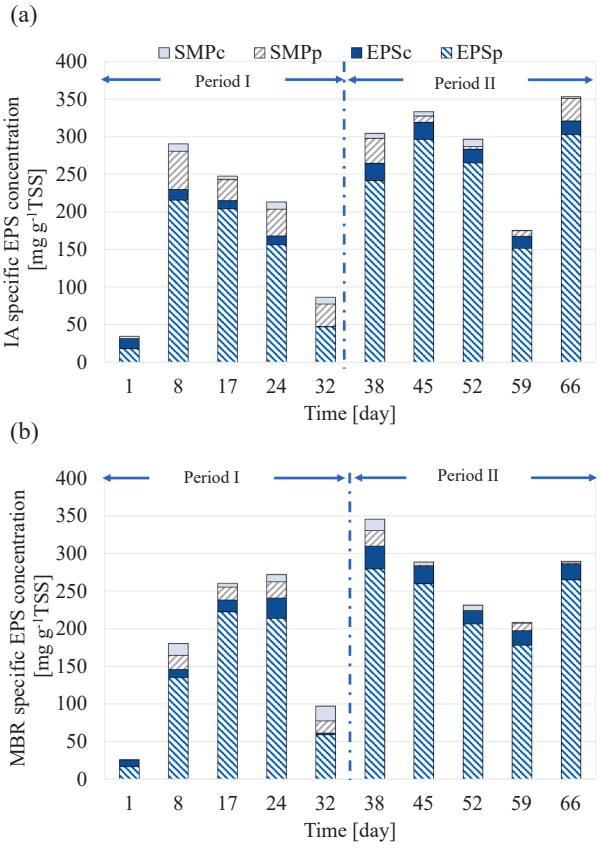

Fig. 3. Specific SMP and EPS concentration in IA reactor (a) and MBR (b) for each experimental period.

comparable results were obtained for TCOD (98 % for both Period I and Period II) and sCOD (86 % and 84 % for Period I and Period II, respectively) (Fig. 2a-b). NH_4-N removal results were comparable during the two periods (average removal efficiency 88 % and 89 % for Period I and II, respectively) (Fig. 2c). In contrast, during Period II an improvement of the TN removal efficiency was obtained (76 % and 83 % for Period I and Period II, respectively), despite the slight increase in TN influent concentration during Period II (average influent concentration 32 mg/L and 37 mg/L for Period I and Period II, respectively) (Fig. 2d). This result was likely due to the role of the attached biofilm (average concentration 1.2 g/L). Indeed, as Waqas et al. [31] suggested, the biofilm structure in IFAS establishes both aerobic and anoxic zones enabling to achieve simultaneous nitrification and denitrification, resulting in a general improvement of TN removal. In terms of nitrogen fractionation (Fig. 2e), one can observe that the average percentage of influent nitrogen use as metabolic nitrogen ($N_{metabolic}$) strongly increased from Period I to Period II (from 21.25 % to 48.5 %). This result was likely due to the increased activity of heterotrophic bacteria, considering the increased influent BOD concentration (Table 1). A slight decrease in nitrogen nitrification efficiency was observed in Period II compared to Period I, with values of 69.6 ± 16.1 % and 88.5 ± 4.5 % respectively. As later reported in paragraph 3.2, this decrease is due to the increased amount of metabolic N rather than a lower efficiency. For the same reason, no significant difference was noted in the denitrification efficiency between Period I and II, at 69.0 ± 12.7 % and 68.6 ± 29.8 % respectively. Overall, effluent N concentration accounted for 7.2 ± 2.9 mg N/L and 5.8 ± 3.4 mg N/L for Period I and II, respectively. The results align with previous literature studies involving intermittent aeration [12,27].

The average PO_4-P removal efficiency increased from Period I to Period II (Fig. 2f). Specifically, during Period I, 31.2 %, of PO_4-P was

Table 3
Average values of heterotrophic and autotrophic kinetic and stoichiometric parameters (in brackets the standard deviation) for Period I and Period II.

Parameter	Symbol	Units	Period I	Period II	
Heterotrophic			*Suspended*	*Suspended*	*Attached*
Max. growth yield	Y_H	[gVSS g^{-1}COD]	0.37 (± 0.04)	0.40 (±0.09)	0.23 (±0.07)
Growth on storage	Y_{STO}	[gVSS g^{-1}COD]	0.48 (± 0.04)	0.54 (±0.06)	0.39 (±0.11)
Decay rate	b_H	[d^{-1}]	1.10 (± 0.27)	0.71 (±0.24)	0.20 (±0.09)
Max. growth rate	μ_H	[d^{-1}]	1.12 (± 3.72)	3.06 (±0.50)	0.93 (±0.17)
Max. removal rate	ν_H	[d^{-1}]	3.01 (± 11.02)	7.74 (±4.22)	4.03 (±0.75)
Net growth rate	μ_H- b_H	[d^{-1}]	0.01 (± 3.45)	2.35 (±0.74)	0.74 (±0.22)
Active fraction	f_X	[%]	22.2 (± 12.64)	32.64 (±0.66)	60.17 (±2.11)
Autotrophic			*Suspended*	*Suspended*	*Attached*
Max. growth yield	Y_A	[gVSS $g^{-1}NH_4$-N]	0.15 (±0.03)	0.17 (±0.04)	0.14 (±0.07)
Decay rate	b_A	[d^{-1}]	0.15 (±0.05)	0.12 (±0.05)	n.a.
Max. growth rate	μ_A	[d^{-1}]	0.17 (±0.09)	0.31 (±0.20)	0.20 (±0.09)
Max. removal rate	ν_A	[d^{-1}]	1.17 (±0.57)	2.08 (±1.76)	1.46 (±0.77)
Nitrification rate	N_R	[$mgNH_4$ L^{-1} h^{-1}]	4.39 (±2.03)	3.78 (±2.76)	1.82 (±0.45)

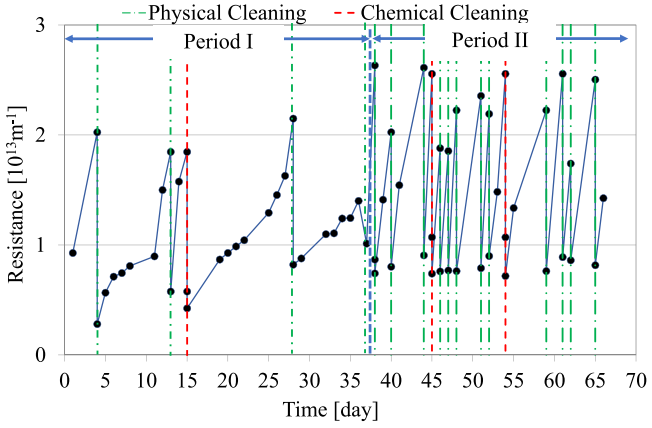

Fig. 4. Trend of total resistance.

removed, increasing to 42.3 % during Period II (Fig. 2f). This latter result is likely due to the role of attached biomass in forming an anoxic/anaerobic zone formation within the biofilm. Indeed, with the increase of biofilm concentration, and consequently of the biofilm anoxic layer, denitrifying phosphate-accumulating organisms (DNPAOs) could grow, thus facilitating the removal of PO_4-P [33].

It is important to note that the amount of N_2O emission, both liquid and gaseous, was strongly reduced from Period I to Period II (Fig. 2e). Indeed, the average emission was 3.5 % of the influent nitrogen during Period I and decreased to 1.9 % during Period II. The results above are confirmed by the dissolved and off-gas N_2O concentration discussed in Section 3.4.

3.2. Operational parameters, sludge properties and kinetic parameters

Table 2 summarizes the observed yield coefficient and SVI values (as average) in Period I and Period II.

As noticeable from the data reported in Table 2, the Y_{obs} increased from Period I to Period II. This result could be likely related to the increased sludge withdrawals carried out to maintain the concentration of suspended biomass close to 3 gTSS/L in Period II, a lower value compared to Period I (3.6 gTSS/L); the reduced TSS concentration in the biological IA reactor could have promoted the increase of the yield coefficient, as better outlined below. This aspect could be of importance, since increased sludge yield could represent a significant concern from both economic and environmental perspectives, due to treatment, transportation and final disposal [6]. From an economic point of view, the management and final disposal of excess sludge might account up to 60 % of the entire WWTP operational cost while, from an environmental perspective, it accounts up to 40 % of GHG emissions produced by WWTPs, thus impacting the CF of the plant [28].

Fig. 3 shows the specific concentration of each EPS compound in the IA and MBR reactors.

Referring to sludge settleability, a slight worsening was observed, with a moderate increase in SVI values. This result may be related to the initial biofilm growth, which corresponds to an intense EPS production to enhance the adhesion of bacterial cells to the suspended plastic carriers.

The EPS values corroborate this behaviour, reported in Fig. 3, highlighting a sensible increase in both IA and MBR reactors from Period I to Period II, respectively.

Concerning the biokinetic behaviour, Table 3 summarises the average values of heterotrophic and autotrophic species for both activated sludge (Period I and Period II) and biofilm (Period II only) obtained throughout the experiments.

Referring to heterotrophic species, it was generally observed an increase in biokinetic parameters of suspended biomass from Period I to Period II, likely related to the increased sludge withdrawals, which could enhance a sort of biomass "renewing" thus increasing the kinetic behavior. The observed increase in the yield coefficient corroborates the result achieved in terms of the observed yield Y_{obs}, as discussed above. The attached biomass's heterotrophic species showed lower values than those of activated sludge, confirming previous experiences with IFAS configurations, where a higher affinity of suspended biomass for organic matter removal was highlighted [9]. Concerning autotrophic species, the achieved values for suspended biomass were more in line with those for biofilm. They were evenly higher compared to the former values achieved in Period I, despite the increased sludge wastage operations (with a simultaneous decrease of the SRT of suspended biomass), which would suggest a "washout" of nitrifiers in the activated sludge. This surprising result could be attributed to the "seeding" effect, where nitrifiers from the biofilm are introduced into the mixed liquor due to biofilm detachment from the carriers. This likely helped replenish the mixed liquor with nitrifying species, aligning well with previous experimental findings [9].

Respirometry results suggested a sort of "specialization" of the two biomasses. Specifically, the suspended biomass exhibited a stronger affinity for removing the organic substrate. In contrast, the attached biomass was more associated with ammonium oxidation. However, the attached biomass also played a role in supporting the activity of nitrifiers within the suspended biomass [21].

3.3. Membrane fouling

Fig. 4 shows the trend of the total resistance (R_T) to the filtration imposed by the membrane for each experimental period. Data from Fig. 4 show that during Period I, four physical and one chemical cleaning were performed to reduce the TMP below the manufacturer's suggested value. The number of cleanings reported above strongly increased

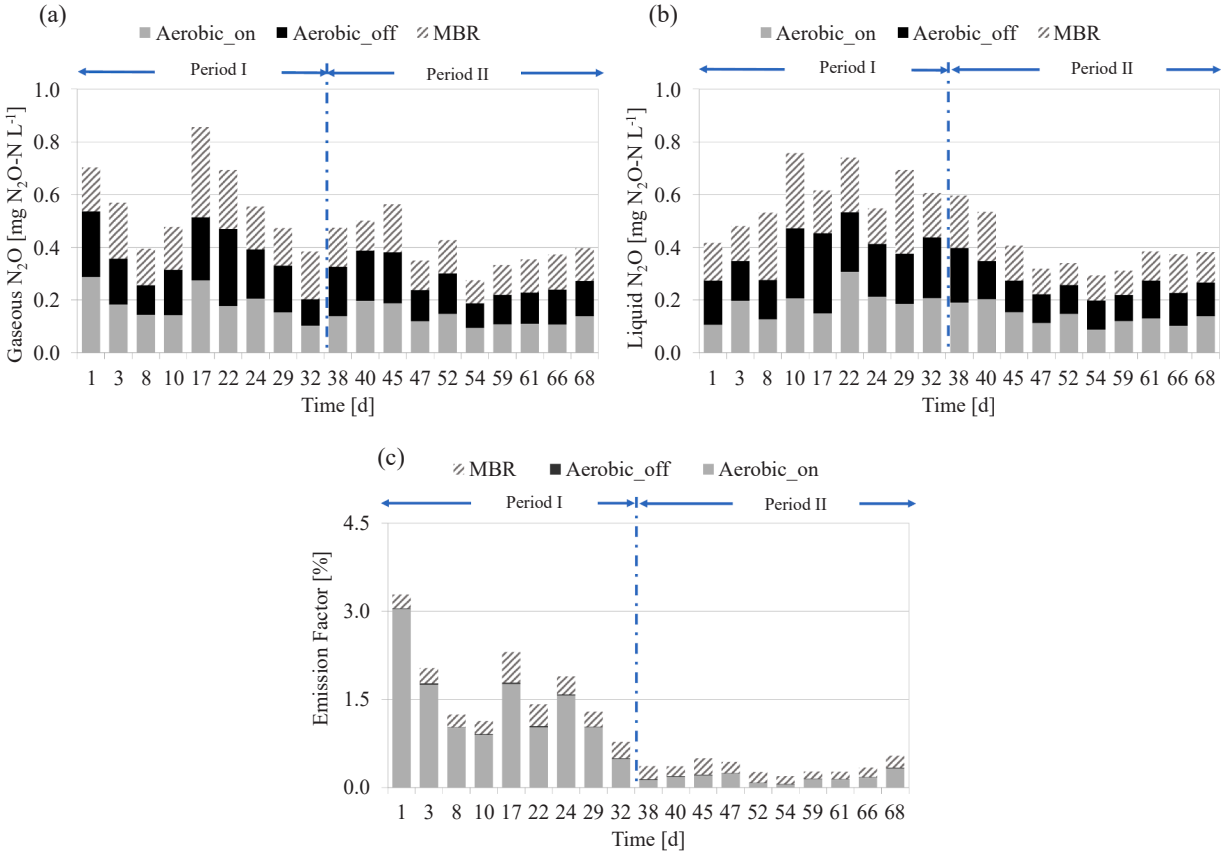

Fig. 5. Gaseous (a) and liquid (b) N_2O concentration measured in the reactors and Emission factor (c).

Table 4
Carbon footprint compounds and N_2O emission factor for each experimental period.

			Period I	Period II
Symbol	Description	Unit	Value	
DE	Direct emissions	kg $CO_{2,eq}$ m^{-3}	0.4	0.2
IE	Indirect emissions	kg $CO_{2,eq}$ m^{-3}	1.4	2.2
DerE	Derived emission	kg $CO_{2,eq}$ m^{-3}	0.7	0.4
CF	**Carbon footprint**	**kg $CO_{2,eq}$ m^{-3}**	**2.5**	**2.8**

during Period II. Indeed, twelve physical and two chemical cleanings were performed during Period II. Furthermore, the maximum value of achieved R_T during Period II was 30 % higher than that of Period I (2.1 $10^{13}m^{-1}$ and 2.7 $10^{13}m^{-1}$ for Period I and Period II, respectively) (Fig. 4). The increased fouling during Period II was due to the increased EPS concentration. The progressive worsening of membrane fouling from Period I to Period II was attributed primarily to the high EPS concentration in Period II.

Specifically, the increase in protein (both EPSp and SPMp) specific concentration during Period II led to an increase in the hydrophobicity of membrane fouling, resulting in a more "bloated" cake layer [15]. This latter circumstance compromised the pre-filter effect of the cake layer, causing an increase in pore fouling [19]. Despite the EPS carbohydrate share in the MBR doubling in Period II (22.2 ± 4.9 mg/gTSS) compared to Period I (12.7 ± 9.2 mg/gTSS), the filtration performance was not improved as reported in the literature [30]. Furthermore, since the detached biofilm is rich in polymeric substances, during Period II, when the IFAS configuration was implemented, the membrane permeability decreased significantly, as reported in previous studies [10,19].

3.4. Greenhouse gas emissions and carbon footprint

Fig. 5 shows the results of N_2O emissions in terms of gaseous and liquid concentration s, as well as the emission factor. The gaseous N_2O concentration during Period II decreased by 30 % compared to that of Period I for all the reactors. Indeed, during Period I the average gaseous N_2O concentration was equal to 0.19 mgN_2O-N L^{-1} in the Aerobic_off and MBR sections and 0.18 mgN_2O-N L^{-1} in the Aerobic_on section (Fig. 5a). During Period II, the average gaseous N_2O concentration was equal to 0.14 mgN_2O-N L^{-1} in Aerobic_off and Aerobic_on sections and 0.12 mgN_2O-N L^{-1} in the MBR section (Fig. 5a). The reduction of N_2O concentration was attributed to improvements in nitrogen transformation processes during Period II and to enhanced heterotrophic kinetics, which enhanced denitrification. This statement was corroborated by the substantial reduction of N_2O concentration in the liquid bulk during Period II. Indeed, during Period I, the average liquid N_2O concentration was around 0.2 mgN_2O-N L^{-1} in all sections. Meanwhile, during Period I, the average liquid N_2O concentration substantially decreased to 0.13 mgN_2O-N L^{-1} in all sections (Fig. 5b).

The reduced N_2O production during Period II resulted in a lower emission factor than in Period I. Indeed, the N_2O emission factor was equal to 1.7 % and 0.35 % of the total nitrogen in the influent during Periods I and II, respectively. The low N_2O emission factor observed is also consistent with the mild C/N ratio obtained (approximately 5 g sCOD/g NH_4^+-N) and the intermittent aeration applied [25]. Although not being appreciable in nitrogen removal due to the higher BOD removed, the N_2O mitigation effect of the biofilm in Period II significantly impacted the process performance [13].

Table 4 presents the values obtained during each experimental period for each emission contribution. As reported in Table 4, the improvement of biological processes during Period II reduced direct (DE) and derived (DerE) emissions. Indeed, the average DE decreased

from 0.4 $kgCO_{2,eq}m^{-3}$ of Period I to 0.2 $kgCO_{2,eq}m^{-3}$ of Period II (Table 4). DerE decreased from 0.7 $kgCO_{2,eq}m^{-3}$ of Period I, to 0.4 $kgCO_{2,\text{ and eq}}m^{-3}$ of Period II (Table 4). Conversely to DE and DerE, IE increased during Period II compared to Period I. This result was debited to the increase in sewage sludge production and membrane fouling during Period II. Indeed, during Period II, the MLSS concentration inside the IA reactor was approximately 3 g/L, aimed at ensuring the growth of the attached biofilm and achieving a total biomass (suspended and attached) concentration of around 3.5 g/L, which is close to the average MLSS concentration of Period I (3.6 g/L). However, during Period II, higher suspended biomass growth was obtained, as confirmed by the observed yield coefficient (Y_{obs}) (Y_{obs} equal to 0.12 gTSS/gCOD and 0.2 gTSS/gCOD during Period I and Period II, respectively). The latter result influenced the IE contribution with a final CF value of 2.5 and 2.8 $kgCO_{2,eq}$ per treated cubic meter during Period I and II, respectively (Table 4). The IFAS system did not significantly alter the energy consumption compared to conventional systems, as indicated by the energy consumption per cubic meter of influent wastewater treated during both periods, at approximately 5.1 kWh/m^3. The result is in line with other conventional pilot-scale systems, with energy consumption around 5 kWh/m^3 [5].

4. Conclusions

This study provides a comprehensive evaluation of two membrane-based wastewater treatment systems, namely MBR and IFAS-MBR, under intermittent aeration conditions. The IFAS system demonstrated significant advantages, specifically improving total nitrogen removal and substantially reducing N_2O emission from 1.7 % to 0.3 % of influent nitrogen. These results underscore the crucial role of biofilm systems in promoting environmental sustainability and compliance with increasingly stringent wastewater treatment regulations. However, operational challenges, such as increased membrane fouling and higher sludge production during IFAS-MBR operation, resulted in higher indirect emissions, which slightly increased the overall carbon footprint from 2.5 to 2.8 kg $CO_{2,eq}/m^3$. This trade-off underscores the need for strategic interventions to enhance operational sustainability. Future research should focus on mitigating these operational drawbacks through advanced membrane technologies, optimised biofilm-carrier interactions and targeted EPS management strategies, in order to maximise the environmental benefits and economic viability of adopting innovative wastewater treatment configurations.

CRediT authorship contribution statement

Giorgio Mannina: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **DI Trapani Daniele:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis, Data curation. **Alida Cosenza:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation. **Paulo Marcelo Bosco Mofatto:** Writing – original draft, Investigation, Formal analysis, Data curation. **Antonio Mineo:** Writing – original draft, Formal analysis, Data curation.

Declaration of Competing Interest

The authors 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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