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Trading-off greenhouse gas emissions and 741/2020 European Union water reuse legislation: An experimental MBR study

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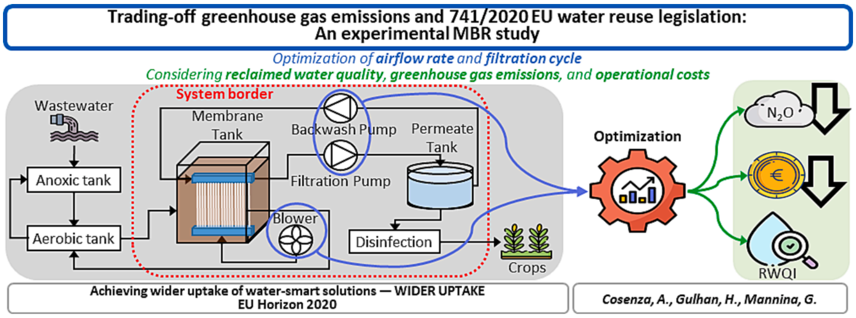
HIGHLIGHTS

- An MBR system was optimized to decrease operational costs and GHG emissions.
- Effluent quality in all trials complied with the EU water reuse legislation.
- The airflow rate had a substantial impact on the operational costs.
- Increased airflow rate decreased N_2O concentrations in the liquid phase.
- The lowest airflow rate and highest backwash frequency was selected as the optimum.

GRAPHICAL ABSTRACT



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ABSTRACT

A trade-off between greenhouse emissions (direct and indirect) and operational costs in the water treatment sector is of great importance, although only few literature studies exist. The paper presents a comprehensive experimental study on a Membrane Bioreactor (MBR) pilot plant at the Water Resource Recovery Facility of Palermo University (Italy). The MBR pilot plant was aimed at reducing carbon footprint while producing water suitable for water reuse in agriculture. Multiple scenarios were assessed to unveil the best operational variables including the assessment of the reclaimed water quality index for water reuse. Results showed the lowest operational costs for the MBR of 5.05 € cent/m^3 with Class B according to 741/2020 European legislation. Results revealed optimised values, in terms of airflow rate and backwash frequency, of 0.8 $m^3/m^2/h$ and 12 times/h, respectively. The highest N_2O emission was measured in correspondence of scenario S5 (airflow rate of 1.6 $m^3/m^2/h$) with 0.40 mg N_2O-$N/m^2/h$ in agreement with previous literature studies. The obtained results could effectively address the operators to find a trade-off between operational costs and water quality.

1. Introduction

The water amount consumed by agricultural activities will increase because agricultural production is expected to expand by 70% in 2050 (The World Bank, 2020). Moreover, extreme climatic events and rain irregularity caused by climate change will make difficult the access to usable water (World Economic Forum, 2020). Treated wastewater is a reliable and continuous water source for areas facing water crises

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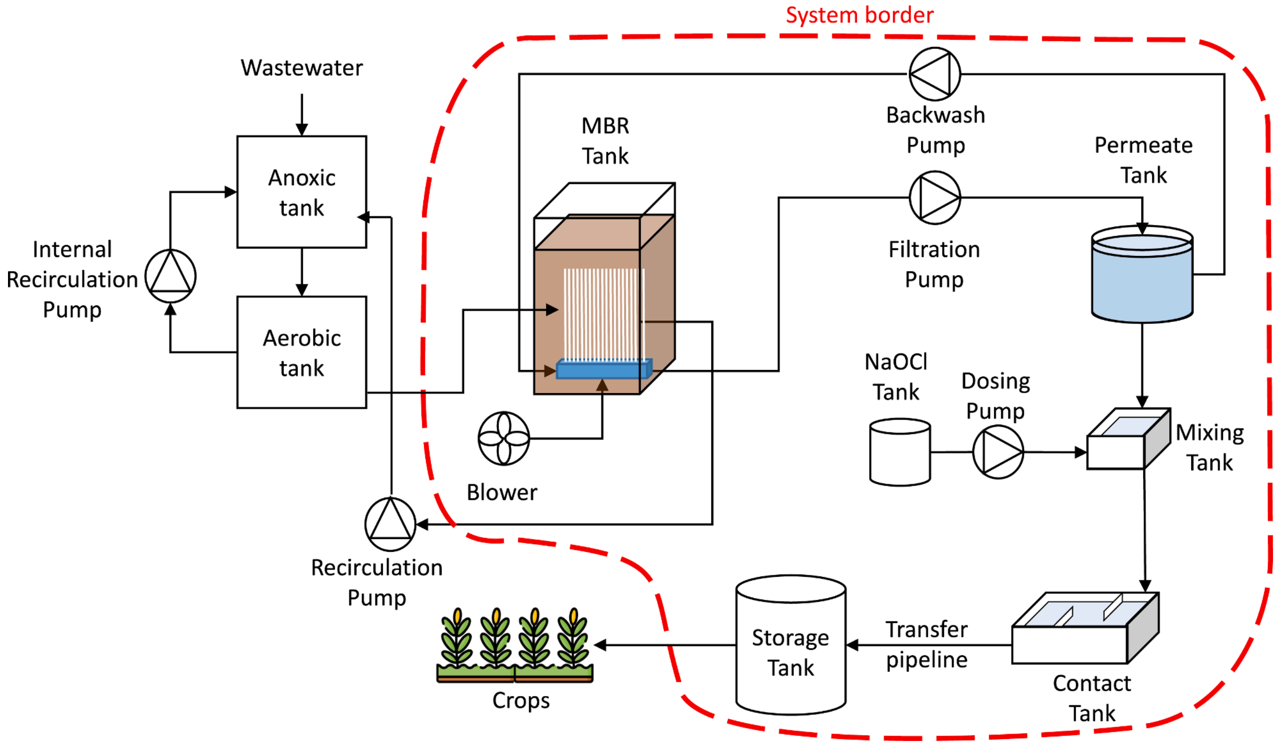


Fig. 1. Flow diagram of the pilot-scale treatment plant; inside the red line the treatment object of this study is shown.

because of climate change (Mannina et al., 2022a). Reusing treated wastewater in agriculture achieves water and nutrient (nitrogen, phosphorus, and potassium) circularity already contained in the water (Ofori et al., 2021; Obaideen et al., 2022; Mannina et al., 2022b). Total suspended solids (TSS), turbidity, biological oxygen demand (BOD_5), Escherichia coli (*E. coli*), and pH are the parameters limited in reclaimed water by the European Union (EU) minimum reclaimed water quality criteria (the EU Regulation 2020/741) (European Council, 2020). Membrane bioreactor (MBR) process has been widely applied and spread over the last decade in the wastewater sector (Wang et al., 2023). MBRs allow to achieve excellent effluent quality and have several advantages over conventional systems (such as higher volumetric loading rates and smaller space requirements) (Judd and Judd, 2011). MBRs also guarantee a partial disinfection of the water towards bacteria having a dimension higher than that of the membrane pores. Xing et al. (2000) observed 100% of TSS and *E. coli* removal in a pilot-scale MBR plant with an external UF membrane that treat urban wastewater. Previous studies showed MBR systems are efficient in removing nutrients, heavy metals, and persistent organic pollutants (Bolzonella et al., 2010). However, the persistence of some contaminants of emerging concern could be realised and even tertiary effluents (Papadaskalopoulou et al., 2015). Racar et al. (2020) achieved 94% of BOD_5 removal with a pilot-scale MBR plant (submerged UF membrane). Tuluk et al. (2022) have recently investigated the possibility of producing water for irrigation by treating domestic wastewater under conditions of low hydraulic retention time in MBR pilot plants (with several configurations). They found that all the investigated configurations produce high effluent quality to be used for irrigation, suggesting the adoption of a hybrid configuration (coupled with biofilm filling material) for reducing power consumption compared to the conventional MBR. Previous literature studies showed that MBR systems are very successful in producing reclaimed water (Smith et al., 2019; Perez et al., 2022). However, operational costs related to membrane fouling are the main drawback of this technology (Perez et al., 2022). These costs are mainly related to the aeration required for the membrane scouring to control the fouling (up to 60% of the total costs) (Judd and Judd, 2011). Backwash and chemical cleaning of membranes are widely applied to minimise (Cornelissen et al., 2007). In view of mitigating fouling and reducing operational costs (both in terms of energy and chemicals), the optimisation of the filtration cycle (filtration and backwashing) plays an important role (Yang et al. 2020). Low frequent backwashing results in very low reclaimed water production since the effluent flow rate reduces due to the membrane fouling (Yang et al., 2021). Moreover, too long filtration times cause high chemical consumption for cleaning and operational costs due to the increase in membrane fouling (Yang et al., 2021). Greenhouse gas (GHG) emissions (direct and indirect) may contribute significantly to climate change and have to be taken into account (Maktabifard et al., 2020; Mannina et al., 2019). Previous studies showed the relevance of the water-energy-GHG emission nexus in WWTPs (Gu et al., 2016; Mannina et al., 2019; Maktabifard et al., 2020; Shao et al., 2021). However, very few studies exist aimed at limiting GHG emissions while producing water suitable for reuse in agriculture. Smith et al. (2019) emphasised the environmental and economic implications of wastewater reuse. They pointed out that repurposing wastewater to replace freshwater rather than discharging it into the environment, leading to a benefit-to-cost ratio increase of more than seven times. However, it is worth noting that previous literature studies focused solely on the energy footprint neglecting GHG emissions related to wastewater treatment and reuse process. Bearing in mind the above considerations, this study presents an experimental study on an MBR, fed with real domestic wastewater, producing water suitable for reuse in agriculture according to the 741/2020 European regulation. The novelty of the study is that multiple scenarios were analysed taking into account GHG emissions with the final aim to find the best operational conditions for carbon footprint minimisation.

2. Material and Methods

2.1. Pilot plant description

An MBR pilot plant was built at the Water Resource Recovery Facility (WRRF) of Palermo University (Mannina et al., 2021a). The pilot plant

Table 1
Experimental design plan.

Parameter	Unit	Step 1			Step 2	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Filtration time (F)	min	9	6	4.5	The best of the first phase	
Backwash time (B)	min	1	0.67	0.5		
F to B ratio	–	9	9	9		
Backwash frequency	times/hour	6	9	12		
Airflow rate	$m^3/m^2/h$	1.2	1.2	1.2	0.8	1.6

consisted of a pre-denitrification scheme (anoxic and aerobic tank) followed by an MBR (Fig. 1). An 80 L/h flow rate of mixed liquor was pumped from the aerobic to the MBR tank. While, 60 L/hwas recycled from the bottom of the MBR to the anoxic reactor. The internal recirculation pump was set to 80 L/h. The pilot plant was continuously fed with real wastewater produced within the University of Palermo Campus (average wastewater flow rate 20 L/h). A Puron® three bundle hollow fibre UF membrane having 1.4 m^2 surface area (pore size: 0.03 μm) was used to separate biomass from treated water (Koch separation solutions). The MBR tank has a 30 L volume and it is equipped with movable covers to collect off-gas samples. The membrane was operated under constant permeate flux conditions.

The membrane fouling was continuously monitored in terms of transmembrane pressure (TMP) and permeate flow rate. Physical and chemical cleanings of the membrane were conducted according to the manufacturer's instructions. The membrane was physically cleaned when absolute TMP was equal to 0.6 bar. In view of performing physical cleaning, the membrane was first removed from the tank and then cleaned with tap water. The membrane was cleaned chemically with NaOCl when the TMP reached the absolute value of 0.8 bar after a physical cleaning. Sodium hypochlorite (NaOCl) was used for membrane chemical cleaning. Specifically, the chemical cleaning membrane (after a physical cleaning) was submerged in a NaOCl solution for 6 h. NaOCl solution was prepared by adding 500 mL NaOCl to 150 L tap water. NaOCl was also adopted as a disinfectant (5 mg Cl_2/L). The disinfection contact time was selected as 30 min. The produced reclaimed water was collected and reused for irrigation of the green area of the Palermo University Campus according to the WRRF within the EU project Wider-Uptake (Mannina et al., 2021a; 2022a; Mannina et al., 2021b).

2.2. Scenario analysis

Table 1 summarises the experimental design and the value of filtration and backwashing times, and the airflow rate provided to the MBR tank. More specifically, experiments were conducted in two steps during which five operating scenarios were investigated. In the first step (scenarios 1 – 3, S1-S3), the filtration cycle was optimised in terms of backwash frequency and in the second step (scenarios 4, 5 - S4, S5) the intensity of aeration was optimised airflow rate provided to MBR tank per membrane surface was 1.2 $m^3/m^2/h$ in the first step of the experimental study. Scenario 1 (S1) has the lowest backwash frequency (6 times/hour) while Scenario 3 (S3) has the highest (12 times/hour). After the best backwash frequency was determined in the first step of the experimental study, 0.8 $m^3/m^2/h$ and 1.6 $m^3/m^2/h$ of airflow rates were tested in Scenario 4 (S4) and Scenario 5 (S5), respectively, in the second step of the study. For scenarios S4 and S5 the same filtration and backwash time as scenario S3 were adopted since it was the best during the first step of the experimental study. Each scenario was completed when chemical cleaning was needed. The pilot plant was operated with the same operational conditions of the biological processes for 2 months and 15 days. The total duration of each scenario was equal to 15 days.

2.3. Analytical methods

Conventional parameters were analysed for the samples collected from the influent, mixed liquor inside the MBR, and permeate. Standard Methods (APHA, 2012) were used to measure total suspended solids (TSS), chemical oxygen demand (COD) (total COD – tCOD), BOD_5, ammonium (NH_4-N), and orthophosphate (PO_4-P). Soluble COD (sCOD) was measured after samples were filtrated via 0.45 μm filters. *E. coli* were measured by using method F as proposed by IRSA – CNR (Italian Decree, 2003). Turbidity was measured by using a portable Hanna (USA) HI93703 turbidimeter. Liquid and gaseous samples were collected from the cover of the MBR tank and N_2O concentration was measured. Specifically, discrete off-gas and liquid samples were withdrawn by using a syringe and injected into vials where the vacuum was previously created.

The method suggested by Mannina et al. (2016) was adopted for dissolved gas sampling. Specifically, 200 mL of mixed liquor from the MBR tank was first sampled and then centrifuged for 5 min under 8000 rpm. After centrifugation, 70 mL of supernatant was inserted into a 125 mL glass bottle where 1 mL of 2 N H_2SO_4 was injected in view to avoid biological reactions. The glass bottle was maintained with gentle stirring. Subsequently, a discrete gas sample was withdrawn from the glass bottle as previously described. Off-gas velocity from the MBR tank was measured by using a TMA-21HW – Hot Wire anemometer in view of evaluating the gas flow rate according to Mannina et al. (2016).

Table 2
Main average influent wastewater features to the main pilot plant and operational conditions per scenario.

Description	Symbol	Unit	S1	S2	S3	S4	S5
Total Suspended Solids	TSS	mg/L	835	489	276	385	485
Ammonium	NH_4-N	mg/L	30	30	27	31	28
Orthophospahe	PO_4-P	mg/L	6	10	11	9	11
Total COD	tCOD	mg/L	1350	960	1125	1210	1152
Filtrated COD	sCOD	mg/L	200	180	186	206	198
Biochemical Oxygen Demand	BOD_5	mg/L	308	238	279	289	276
Mixed Liquor Suspended Solids in aerobic tank	$MLSS_{AER}$	g/L	3.8	4.0	4.1	3.9	4.1
Mixed Liquor Suspended Solids in anoxic tank	$MLSS_{ANOX}$	g/L	3.0	3.1	3.3	3.2	3.1
Mixed Liquor Suspended Solids in MBR tank	$MLSS_{MBR}$	g/L	4.5	4.8	5.0	4.9	5.0
Hydraulic Retention Time	HRT*	hours	20.0	20.0	20.0	20.0	20.0
Sludge Retention Time	SRT*	days	40.0	40.0	40.0	40.0	40.0
Temperature	T	°C	25.0	25.0	24.0	23.0	23.0

* refer to the whole pilot plant.

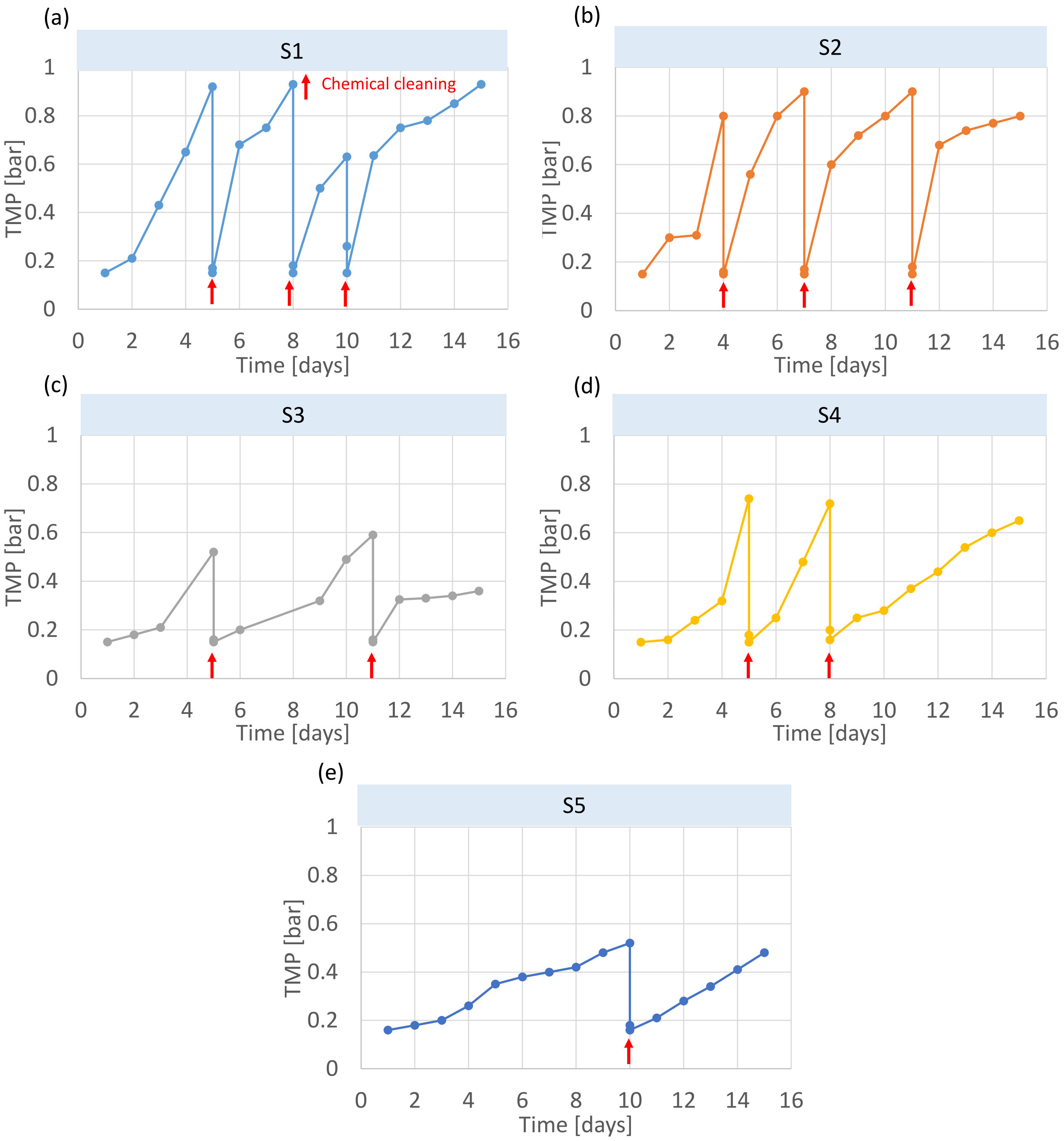


Fig. 2. Trend of TMP for Scenario S1 (a), S2 (b), S3 (c), S4 (d) and S5 (e).

N_2O of all samples was measured by using a Gas Chromatograph (Thermo Scientific™ TRACE GC) equipped with an Electron Capture Detector. The off-gas flow rate was measured according to Mannina et al. (2017). Table 2 summarises the features of the influent wastewater and operational conditions.

2.4. Evaluation criteria

2.4.1. Reclaimed water quality index

The reclaimed water quality index (RWQI) was used to compare the treatment performance of the MBR (Cosenza et al., 2022). The desired (namely, nitrogen and phosphorus) and undesired (namely, TSS, BOD_5, turbidity and *E. coli*) parameters were selected according to the European Commission criteria for minimum quality of reclaimed water (Regulation 2020/741). Weight factors for undesired compounds were selected as −0.29 for E. *coli* and −0.14 for BOD_5, TSS and turbidity (Cosenza et al., 2022). Similarly to previous studies, the weight factor of E. *coli* was assigned higher than the other compounds since it is the direct indicator of faecal pollution (Cosenza et al., 2022). If TN and TP were over Italian discharge criteria (for TN: 35 mg/L; for TP: 10 mg/L), then the exceeding amount of TN and TP were calculated as undesired compound and weight factors were −0.14 for undesired TN and TP (Italian Decree, 2003). For desired compounds of TN and TP (when the concentrations were below Italian discharge limits) the weight factors were considered, according to previous studies, equal to 0.5 (among others, Cosenza et al., 2022).

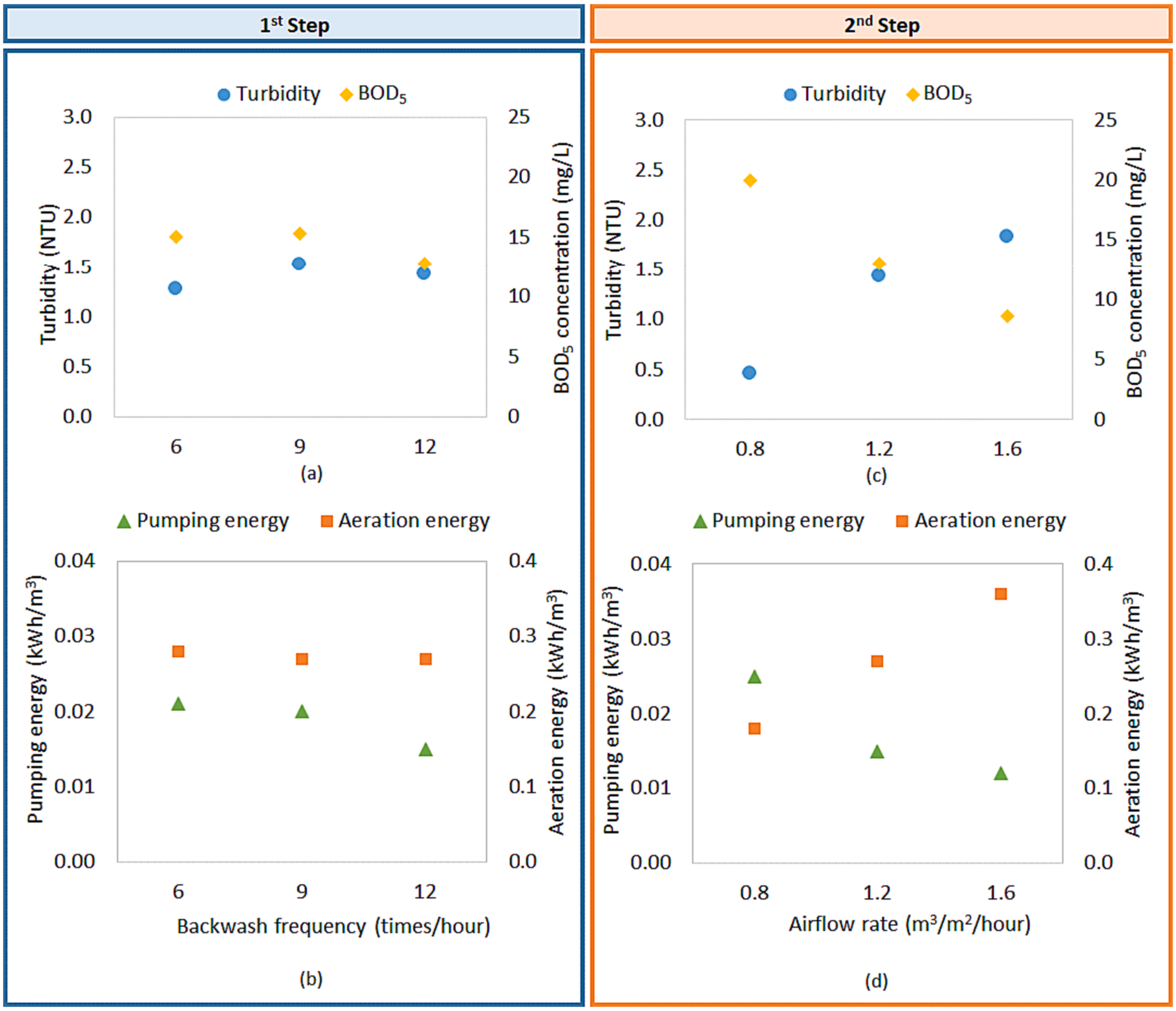


Fig. 3. Backwash frequency effect on (a) turbidity and BOD_5 concentrations in the permeate (b) and pumping energy; airflow rate effect on (c) turbidity and BOD_5 concentrations in the permeate (d) and pumping energy.

2.4.2. *GHG emissions*

Direct GHG emissions were evaluated as the total N_2O-N concentration in the liquid and gaseous samples withdrawn from the MBR tank.

2.4.3. *Operational costs*

The operational costs included the chemical and energy costs of the MBR plant. The unit cost of chemical cleaning was taken as 0.127 €/cleaning. The cost of NaOCl solution (14% of active chlorine) is 23 €/L (EMPLURA®). The energy cost is the sum of pumping (filtration and backwash) energy, E_{pump} and aeration energy.

Specifically, E_{pump} was calculated according to the following Equation 1 (Cosenza et al., 2022).

$$E_{pump} = \frac{1}{t_1 - t_0} \sum_{t_0}^{t_1} \frac{TMP\, Q_{eff}(t)}{3600\,\eta} [\mathrm{kW}] \tag{1}$$

where: TMP [kPa] is the transmembrane pressure, Q_{eff} [m^3/h] is the effluent flow rate η is the pump efficiency and operation t_1-t_0 is the operation time.

E_{aer} was calculated according to the following Equation 2 (Cosenza et al., 2022).

$$E_{aer} = \frac{w\,R\,T}{29.7\,(0.283)\,e}\left(\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right)[\mathrm{kW}] \tag{2}$$

where: w [kg/s] is the mass flow of the air, R [8.314 kJ/kmol/K] is the gas constant for air, T [K] is the air temperature, e [-] is the blower efficiency, while p_1 and p_2 [atm] are the inlet and outlet pressure of the blower, respectively.

The electricity price was assessed as 0.28 €/kWh according to the Italian fare.

3. Results and discussion

3.1. *Effect of backwash frequency*

In the first step of the experimental study, the backwash frequency was increased from 6 times/hours to 9 times/hours and 12 times/hours in S1, S2, and S3, respectively. Fig. 2 shows the trend of TMP for each scenario.

In Fig. 3, the results of the first and second steps of the study are shown as average values over the entire scenario duration.

Results revealed a decreasing trend in maximum TMP values with the increase in backwash frequency. The above results might be related to a decreased cake layer thickness with increasing backwash frequency. Specifically, maximum TMP values measured in S1, S2, and S3 were 0.93 bar, 0.90 bar, and 0.59 bar, respectively (Fig. 2a-c). This latter result influenced the pumping energy requirement. Indeed, as shown in Fig. 3a, the pumping energy decreased from 0.021 kWh/m^3 to 0.015

Table 3
Effluent characterisation of scenario.

Parameter	Unit	S1	S2	S3	S4	S5	Class A	Class B
Backwash frequency	times/hour	6	9	12	12	12	–	–
Airflow rate	$m^3/m^2/h$	1.2	1.2	1.2	0.8	1.6		
TSS	mg/L	ND	ND	ND	ND	ND	≤10	≤35
Turbidity	NTU	1.3 ± 0.4	1.5 ± 0.5	1.4 ± 0.3	0.5 ± 0.7	1.8 ± 2.3	≤5	–
BOD_5	mg/L	15.0 ± 3.1	15.3 ± 2.1	12.8 ± 3.4	20 ± 2.4	8.6 ± 1.8	≤10	≤25
E. coli	cfu/100 mL	ND	ND	ND	ND	ND	≤10	≤100
NH_4-N	mg/L	5.2 ± 0.7	4.0 ± 2.0	1.6 ± 1.0	2.4 ± 1.5	3.8 ± 3.6	–	–
PO_4-P	mg/L	4.7 ± 0.3	5.5 ± 0.6	9.9 ± 5.0	8.0 ± 1.2	13.8 ± 8.3	–	–

ND: Not detected.

kWh/m^3 with the increased backwash frequency. Accordingly, chemical cleaning cost decreased with increased backwash frequency from 0.0315 €/m^3 to 0.0198 €/m^3. Backwash frequency did not affect particle capture of the UF membrane in line with the literature (Mannina and Cosenza, 2013). Indeed, turbidity values measured in the permeate were relatively stable in the range of 1.2–1.6 NTU (Fig. 3a). The low turbidity values (<1 NTU) in the permeate of the MBR are expected since particle retention of membrane filtration is quite high (Racar et al., 2020; Arévalo et al., 2009; Verrecht et al., 2012; Zhang et al., 2013). Backwash frequency did not affect the biological process in the MBR tank as well. BOD_5 concentrations in the permeate were in the range of 17–22 mg/L (Fig. 3a). In line with this study, Racar et al. (2020) measured 25 ± 14 mg/L of BOD_5 in the permeate of the MBR system treating domestic wastewater. NH_4-N removal efficiencies were 23%, 21%, and 25%, S1, S2, and S3, respectively. The low NH_4-N removal efficiencies in the MBR suggest that the low HRT of the MBR reactor (namely, 1.5 h) limited the nitrification of the remaining NH_4-N after the bioreactors. In conclusion, since scenario S3 (with the highest backwash frequency of 12 times/hour) had the lowest energy cost and chemical cleaning requirement, it was selected as the optimum and compared during the second step with S4 and S5 results.

3.2. *Effect of the airflow rate*

In the second step of the experimental study, the backwash frequency was kept 12 times/hours and two airflow rates were tested (namely, 0.8 $m^3/m^2/h$ and 1.6 $m^3/m^2/h$ for scenario S4 and S5, respectively). Fig. 3 shows turbidity and BOD_5 concentration in the permeate with respect to the variations in airflow rate. Permeate turbidity showed a similar trend with airflow rate increase. However, the variation of measured turbidity values was very low (namely, S4: 0.5 NTU; S5: 1.8 NTU). Increased aeration in the MBR tank decreased BOD_5 concentration from 20.0 mg/L to 14.3 mg/L in the permeate. Similarly to previous studies, increased airflow rate detached the cake layer from the membrane surface and caused a decrease in TMP values from 0.74 bar to 0.52 bar (Fig. 2d-e) (Liu et al., 2021). Since cake layer attachment to the membrane surface decreased, less chemical cleaning was applied in S5 (1.6 $m^3/m^2/h$ of airflow) with 0.015 €/m^3 of cleaning cost. Similarly, pumping energy decreased from 0.025 kWh/m^3 to 0.012 kWh/m^3 with increasing airflow. On the other hand, 0.18 kWh/m^3 of increase in aeration energy was more significant than the decrease in pumping energy (Fig. 3d). The sum of energy consumption of pumping and aeration of the MBR tank is 0.30 kWh/m^3 for S1, 0.29 kWh/m^3 for S2 and S3, 0.21 kWh/m^3 for S4 and 0.37 kWh/m^3 for S5. Results are aligned with previous literature studies reporting energy consumption of the membrane zone of MBR units in full-scale treatment plants in China as 0.23 kWh/m^3 (Xiao et al., 2014).

3.3. *Overall evaluation*

Table 3 summarises the effluent characterisation of each scenario compared with the EU minimum reclaimed water quality criteria for Class A and Class B waters. TSS concentrations in the permeate of each scenario were 0 mg/L, and turbidity values were in the range of 0.5–1.8 NTU in line with literature reporting turbidity in the order of < 2 NTU (Xing et al., 2000). TSS, turbidity, and *E. coli* values of all scenarios were below limited values by Class A criteria. However, only in S5 the concentration of BOD_5 in the permeate was below Class A limits. BOD_5

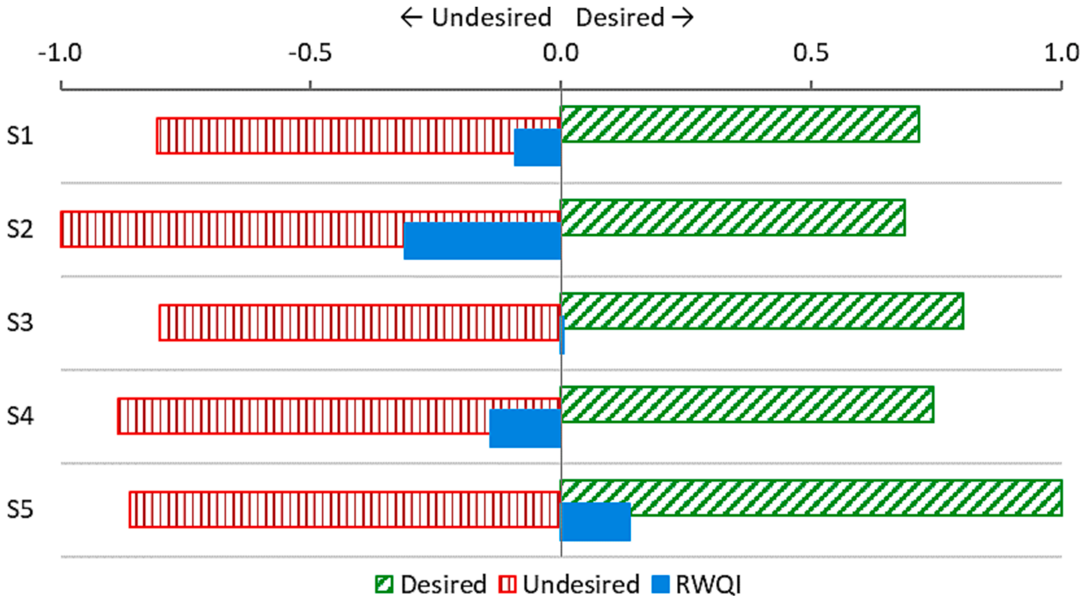


Fig. 4. Quality indexes of each scenario: (a) desired parameters; (b) undesired parameters; (c) RWQI.

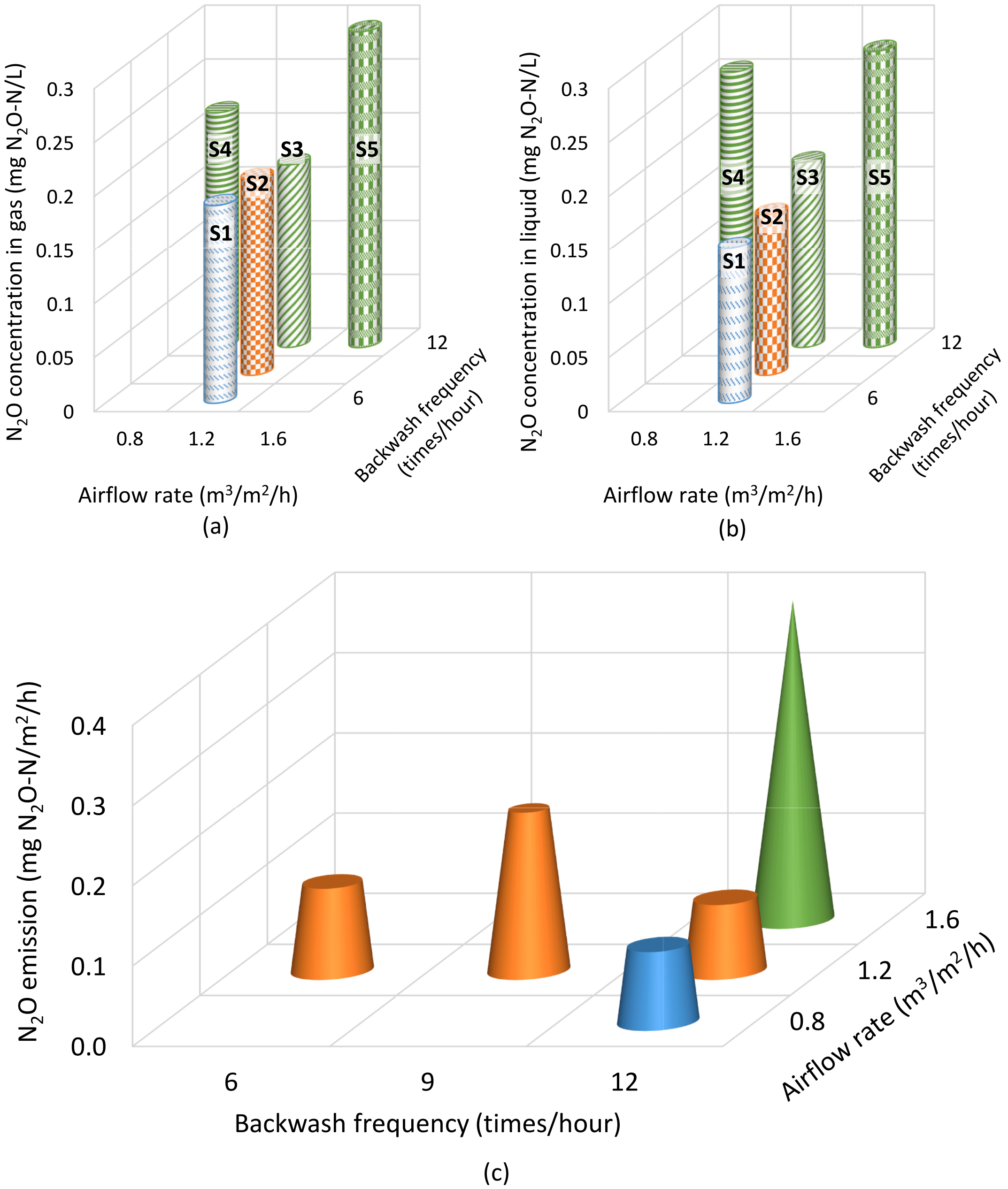
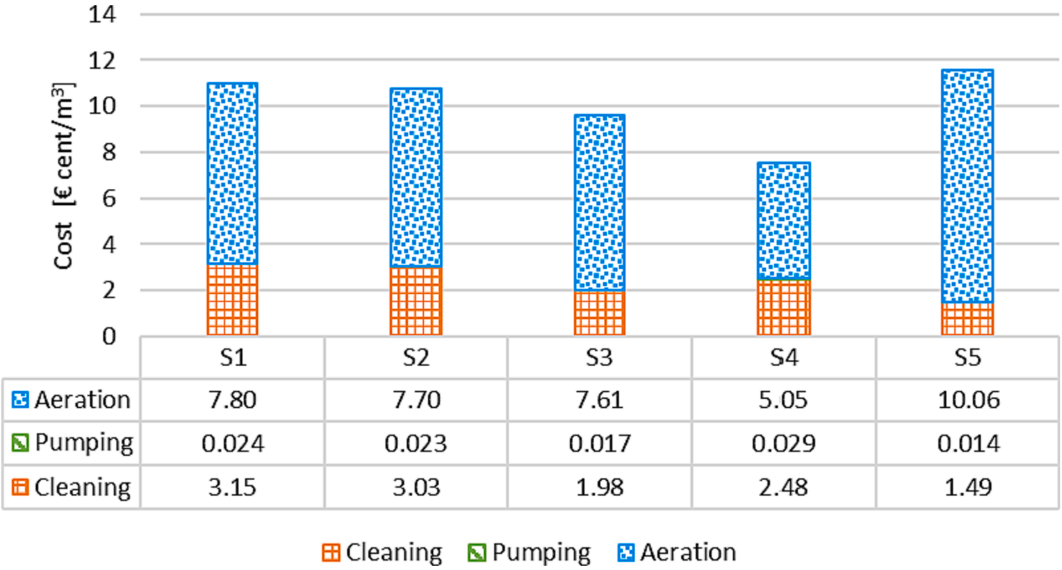


Fig. 5. N_2O concentrations in gas (a), liquid (b) samples and N_2O emissions from MBR (c).

concentrations in the permeate of S1, S2, S3, and S4 scenarios were above Class A limits but suitable for Class B. Class A quality reclaimed water is suitable for all types of crops (root crops, above low-ground crops, and high-ground crops) consumed raw. On the other hand, Class B quality reclaimed water is suitable for above low-ground and high-ground crops.

The RWQI of each scenario is given in Fig. 4. RWQI is a tool to compare reclaimed waters with different qualities by considering desired and undesired parameters to project the benefits of nitrogen and phosphorus in reclaimed water from the agricultural point of view. Due to the high NH_4-N and PO_4-P concentrations observed in the permeate of S5, it has the highest desired value (1.0). In contrast, S2 has the lowest desired value of 0.69. On the other hand, for undesired parameters, S3 and S1 have the lowest absolute values of 0.80 and 0.81. S5, with the highest airflow to the MBR tank resulted in the highest RWQI (namely, 0.14).

Fig. 5 shows N_2O concentrations measured in gas and liquid samples collected and N_2O emissions from the MBR tank of each scenario. Increasing backwash frequency from 6 times/hour to 12 times/hour did not affect N_2O concentrations of gas samples (S1: 0.18 mg N_2O-N/L; S2: 0.18 mg N_2O-N/L; S3: 0.17 mg N_2O-N/L) (Fig. 5a). Similarly, only a slight increase in N_2O concentrations in the liquid samples was observed with increasing backwash frequency (S1: 0.14 mg N_2O-N/L; S2: 0.15 mg N_2O-N/L; S3: 0.17 mg N_2O-N/L). However, airflow rate change caused N_2O concentration variations in gas and liquid samples. Dissolved air concentration is known to be one of the important parameters that affect N_2O emission from activated sludge systems since it affects the activity of nitrifiers/denitrifiers and N_2O stripping from the liquid phase to the gas phase (Kim et al., 2010). In this study, the aeration to nitrification (aeration) tank of the activated sludge system before the MBR tank was kept constant during operation and the dissolved oxygen concentration in the MBR tank was over 3 mg/L for all scenarios. However, the dynamic influent wastewater characterisation, especially the dynamic carbon-to-nitrogen ratio, that was fed to the upstream system resulted in



	S1	S2	S3	S4	S5
Aeration	7.80	7.70	7.61	5.05	10.06
Pumping	0.024	0.023	0.017	0.029	0.014
Cleaning	3.15	3.03	1.98	2.48	1.49

Fig. 6. Operational costs of each scenario.

different N_2O loads to the MBR tank. Therefore, the change in airflow rate to the MBR tank affected N_2O gas stripping from the liquid phase to the gas phase but not the N_2O production in the MBR tank. The biomass activity did not change drastically with increasing airflow rate (Fig. 3c). The fraction of N_2O concentration in the liquid phase to gas phase decreased from 1.01 to 0.94 when the airflow rate increased from 0.8 $m^3/m^2/h$ (S4) to 1.6 $m^3/m^2/h$ (S5). Accordingly, increased aeration increased N_2O emission to the atmosphere (Fig. 5c). The highest N_2O emission was measured in S5 with 0.40 mg N_2O-N/m^2/h (Fig. 5c). While, for S3 and S4 the N_2O emission of 0.1 mg N_2O-N/m^2/h and 0.085 mg N_2O-N/m^2/h was obtained, respectively (Fig. 5c).

In Fig. 6, the normalnormalised respect to the m^3 of treated water) operational costs for each scenario are shown. Data from Fig. 6 shows that during step 1, scenario S3 (with the highest backwash frequency – 12 times/hour) provided the lowest cost (total cost of 9.6 € cent/m^3). This latter result was strongly influenced by the lowest cost due to the chemical cleaning (1.98 € cent/m^3) during S3. However, the absolute lowest operational cost was obtained during scenario S4 during which the lowest airflow rate was adopted (0.8 $m^3/m^2/h$), thus strongly reducing the cost due to the aeration (5.05 € cent/m^3). Therefore, in terms of operational cost, the optimal condition is that of scenario S4.

4. Conclusions

Multiple airflow rates and backwash frequencies were tested to optimise the operational costs and GHG emissions of an MBR pilot plant producing treated water for agriculture reuse according to 741/2020 European Legislation. Results showed a significant influence on the operational costs of the aeration flow rate for mitigating membrane fouling. In particular, the best operating condition was selected as having the lowest airflow rate (namely, 0.8 $m^3/m^2/h$) and the highest backwash frequency (namely, 12 times/h). For the best operating condition, the lowest operational cost (5.05 € cent/m^3) and reclaimed water having features of Class B according to European legislation were obtained.

CRediT authorship contribution statement

Alida Cosenza: Conceptualization. **Hazal Gulhan:** Conceptualization. **Giorgio Mannina:** Conceptualization.

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.

Data availability

The data that has been used is confidential.

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