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Interlinkages between operational conditions and direct and indirect greenhouse gas emissions in a moving bed membrane biofilm reactor

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PRIN
Research project of national interest
2012
Green House Gases emissions from Wastewater Treatment Plants

Introduction

Wastewater treatment entails:

- direct emissions of greenhouse gases (GHGs), such as nitrous oxide (N_2O)
- indirect emissions resulting from power requirements

N_2O Unwanted even at small levels due to the high global warming potential 310 higher than CO_2

N_2O Production Pathways

Nitrification

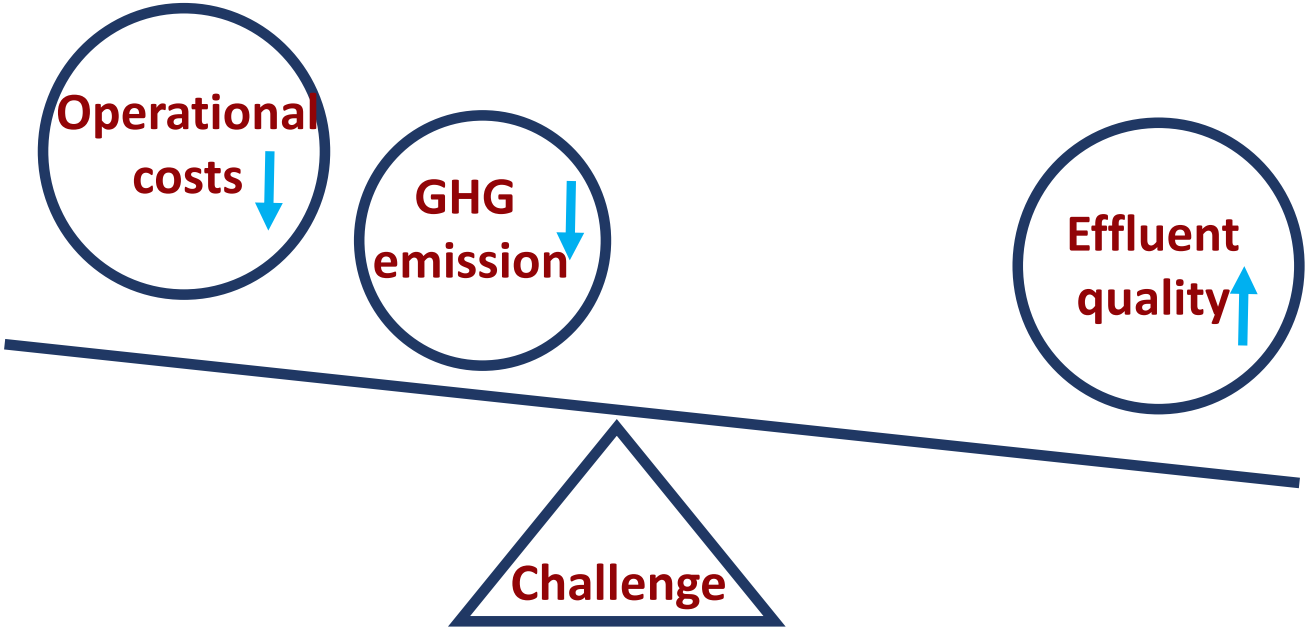
- ✓ reduction of NO_2^- as terminal electron acceptor to N_2O (AOB denitrification)
- ✓ incomplete oxidation of hydroxylamine (NH_2OH) to NO_2

Denitrification

- ✓ intermediate of the incomplete heterotrophic denitrification

Introduction

Process operations aimed at the reduction of N_2O could conflict with the effluent quality and increase the operational costs



To identify GHG mitigation strategies as trade-off between operational costs and effluent quality index is a very ambitious challenge

Aim

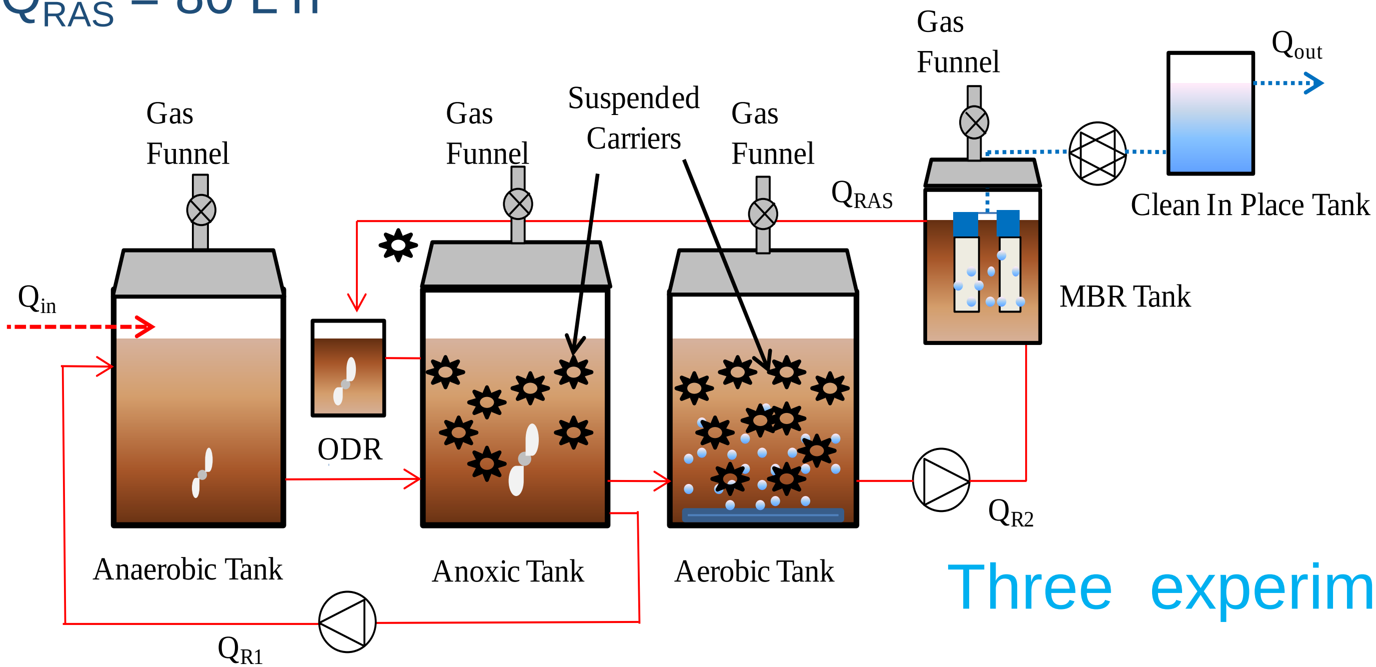
Simple model for interlinkage among operational conditions/influent features/effluent quality and emitted N_2O.

Performing a multivariate analysis
+
University Cape Town (UCT) moving bed (MB) membrane bioreactor (MBR) pilot plant.

Methods

Pilot plant

$Q_{IN} = 20\ L\ h^{-1}$
$Q_{R1} = 20\ L\ h^{-1}$
$Q_{RAS} = 80\ L\ h^{-1}$
$Q_{R2} = 100\ L\ h^{-1}$
$Q_{OUT} = 20\ L\ h^{-1}$



Three experimental phases:

Phase I: SRT = ∞
Phase II: SRT = 30 days
Phase III: SRT = 15 days

150 days of experimentation

Mixture of real and synthetic wastewater!

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Pilot plant

PURON 3 bundle ultrafiltration module (pore size 0.03 µm, surface 1.4 m^2)

AMITECH carriers in anoxic and aerobic reactors with a 15 and 40% filling fraction respectively

Measured data

TSS, VSS, COD_{TOT}, COD_{SOL}, $N\text{-}NH_4$, $N\text{-}NO_3$, $N\text{-}NO_2$, TN, TP, $P\text{-}PO_4$, DO, pH, T,

$N\text{-}N_2O$ as gas and dissolved

Two time per week in each tank

Indirect emissions

The **Operational Costs (OCs)** were evaluated using conversion factors (Mannina and Cosenza, 2015):

$$OC = \left(Pw + Peff\right) \cdot \gamma_e + EF$$

Pw [kWh m^{-3}] energy required for the aeration

Peff [kWh m^{-3}] energy required for permeate extraction

$\gamma_{power,GHG}$ γ_e conversion factors, 0.7 gCO_{2eq} and 0.806 € kWh^{-1}

EF [€ m^{-3}] cost of the effluent fine including N_2O

Indirect emissions

The **effluent fine (EF)** was evaluated using:

$$EF = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{1}{Q_{IN}} \sum_{j=1}^{n} \left[\begin{array}{l} Q_{OUT} \cdot \Delta\alpha_j \cdot C_j^{EFF} + \left(Q_{OUT}\right) \cdot \\ \left(\beta_{0,j} + \left(C_j^{EFF} - C_{L,j}\right) \cdot \left(\Delta\beta_j - \Delta\alpha_j\right)\right) \end{array} \cdot \left(Heaviside\left(C_j^{EFF} - C_{L,j}\right)\right) \right] dt$$

Q_{IN} and Q_{OUT} are the influent and effluent flow, respectively;
$\Delta\alpha_j$ is the slope of the curve EF versus C_j^{EFF} when $C_j^{EFF} < C_{L,j}$ (in this case, the function Heaviside =0);
$\Delta\beta_j$ represents the slope of the curve EF versus C_j^{EFF} when $C_j^{EFF} > C_{L,j}$ (in this case, the function Heaviside =1);
$\beta_{0,j}$ are the increment of the fines for the latter case.

Indirect emissions

The **effluent quality index (EQI)** was evaluated using:

$$EQI = \frac{1}{T \cdot 1000} \int_{to}^{t1} \left(\begin{matrix} b_{COD} \cdot COD_{TOT} + b_{TN} \cdot TN + b_{PO} \cdot PO + \\ b_{N2Ogas} \cdot N_2O_{gas} + b_{N2O,L} \cdot N_2O_L \end{matrix} \right) \cdot Q_{OUT} \cdot dt$$

β_{COD}, β_{TN}, β_{PO}, β_{N2Ogas} and $\beta_{N2O,L}$ are the weighting factors of the effluent COD_{TOT}, TN, PO, liquid N_2O in the permeate and gaseous N_2O.

Multiregression analysis

Performed to point out general relationships for the $N\text{-}N_2O$ and the plant operation conditions or the available measured data

Two type of analysis

Simple linear regression	Complex regressions

Simple linear regression

$$Y = c_1 \cdot X_1 + c_2$$

N_2O-N $flux_{ANAER}$ (N_2O-N flux emitted from the anaerobic tank)

N_2O-N $flux_{ANOX}$ (N_2O-N flux emitted from the anoxic tank)

N_2O-N $flux_{AER}$ (N_2O-N flux emitted from the aerobic tank)

N_2O-N $flux_{MBR}$ (N_2O-N flux emitted from the MBR tank)

N_2O-N $dissolved_{OUT}$ (N_2O-N permeate dissolved concentration)

Dependent variables

Y = dependent variable; X_1 = independent variable; c_1, c_2 regression coefficients

Complex regressions

$$Y = c_1 \cdot X_1 + \cdots + c_n \cdot X_m$$

Multiple linear (LINm)

$$Y = c_1 \cdot X_1^{c2} \times \cdots \times c_{n-1} \cdot X_m^{cn}$$

Multiple exponential (EXP)

$$Y = c_1 \cdot X_1^{c2} + \cdots + c_{n-1} \cdot X_m^{cn}$$

Sum of exponential (SumEXP)

$\sum N_2O$-N flux (sum of the N_2O-N flux emitted from each tank)
N_2O-N dissolved$_{OUT}$ (N_2O-N permeate dissolved concentration)

} Dependent variables

Y = dependent variable; $X_1,\ldots,X_m$= independent variable; $c_1,\ldots,c_n$ regression coefficients

Independent variables

Influent concentration

$COD_{TOT, IN}$, $N\text{-}NH_{4,IN}$, $P_{TOT,IN}$, $P\text{-}PO_{4,IN}$, C/N

Effluent concentration

$COD_{TOT,OUT}$, $BOD_{5,OUT}$, $N\text{-}NH_{4,OUT}$, $N\text{-}NO_{3,OUT}$, $NO_2\text{-}N_{,OUT}$, $P\text{-}PO_{4,OUT}$

Intermediate concentration

$N\text{-}NO_{2\_AER}$, $N\text{-}NO_{2\_ANOX}$, DO_{AER}, DO_{ANOX}, pH_{AER}, pH_{ANOX}, DO_{MBR}

Performance indicators

$\eta_{COD,BIO}$, $\eta_{COD,TOT}$, η_{NITR}, η_{DENIT}, ηN_{TOT}, ηP

Operational conditions

TSS*, SRT, Biofilm*

Numerical settings

10,000 Monte Carlo simulations varying coefficients

Evaluation of Nash and Sutcliffe efficiency for each simulation

$$Efficiency = 1 - \frac{\sum_{i=1}^{n}(Y_{meas,i} - Y_{sim,i})^2}{\sum_{i=1}^{n}(Y_{meas,i} - Y_{aver,meas,i})^2}$$

$Y_{meas,i}$ = measured value of the ith dependent state variable; $Y_{sim,i}$ = simulated value of the ith dependent state variable; $Y_{aver,meas,i}$ = average of the measured values of the ith dependent state variable

Results

Simple linear regression analysis

Maximum efficiency

Varying the SRT different variables can be adopted to predict the N_2O

NO_2 accumulation influence the N_2O production

N_2O dissolved in the permeate depend on COD_{OUT}

Phase		Dependent variables				
					N_2O-N $flux_{MBR}$	N_2O-N $dissolved_{OUT}$
I	Independent variable	TSS	NO_2-N_{ANOX}	NO_2-N_{ANOX}	NH_4-N_{IN}	NO_3-N_{OUT}
	Efficie	[illegible]	[illegible]	[illegible]	2	0.1
II	Indepen variab	[illegible]	[illegible]	[illegible]	TR	COD_{OUT}
	Efficie	[illegible]	[illegible]	[illegible]	26	0.72
III	Independent variable	pH_{AER}	Biofilm	Biofilm	PO_4-P_{OUT}	NO_2-N_{AER}
	Efficiency	0.12	0.36	0.67	0.52	0.94

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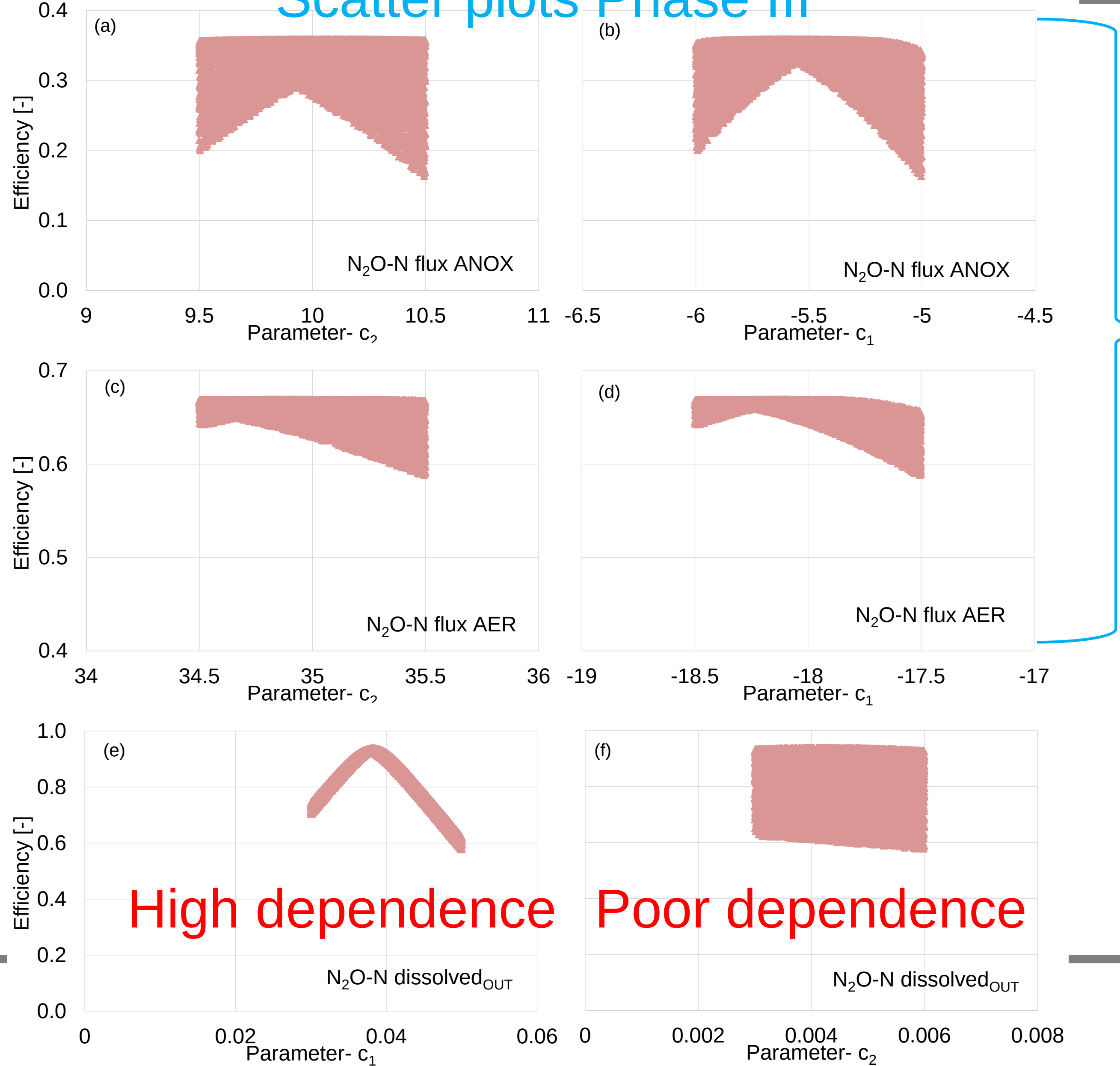
Simple linear regression analysis

Scatter plots Phase III



Combining effect

Complex multiregression analysis

LINm - Maximum efficiency

	$\sum N_2O$-N flux	N_2O-N dissolved$_{OUT}$
	Efficiency	Efficiency
Independent variable	**0.015**	**0.244**
C/N		
N-$NH_{4,IN}$		
TSS		
Biofilm		
SRT		
DO_{AER}		
N-NO_{2_AER}		
pH_{AER}		
DO_{ANOX}		
N-NO_{2_ANOX}		
pH_{ANOX}		

LINm poorly reproduces the measured data for $\sum N_2O$-N flux (efficiency 0.015). Efficiency obtained for the N_2O-N dissolved$_{OUT}$ is slightly higher than for $\sum N_2O$-N flux (equal to 0.244)

Complex multiregression analysis

EXP and SumEXP - Maximum efficiency

	EXP		SumEXP	
	$\sum N_2O$-N flux	N_2O-N dissolved$_{OUT}$	$\sum N_2O$-N flux	N_2O-N dissolved$_{OUT}$
	Efficiency	Efficiency	Efficiency	Efficiency
Independent variable	**0.125**	**0.164**	**0.198**	**0.178**
C/N				
C/N				
N-$NH_{4,IN}$				
N-$NH_{4,IN}$				
TSS				
TSS				
Biofilm				
Biofilm				
SRT				
SRT				
DO_{AER}				
DO_{AER}				
N-NO_{2_AER}				
N-NO_{2_AER}				
pH_{AER}				
pH_{AER}				
DO_{ANOX}				
DO_{ANOX}				
N-NO_{2_ANOX}				
N-NO_{2_ANOX}				
pH_{ANOX}				
pH_{ANOX}				

Poor efficiency values obtained for both the investigated dependent variables

Conclusions

- ✓ Reasonable agreements for simple regression equations
- ✓ Dependency of N_2O flux with SRT and plant sections
- ✓ SRT of Phase III makes the conditions of N_2O production more sharped
- ✓ None of the investigated equations for complex multivariate analysis is able to provide satisfactory efficiencies

Message to take home!

The interactions among the key factors affecting the N_2O make difficult to establish an unique equation valid for different operational conditions for predicting N_2O

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Thank you for your attention

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