DEMOCRITUS UNIVERSITY OF THRACE
DEPARTMENT OF ENVIRONMENTAL ENGINEERING
LABORATORY OF WASTEWATER MANAGEMENT AND TREATMENT TECHNOLOGIES

Advanced process control in activated sludge systems

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Outline of the thesis

- **Introduction**
- **Instrumentation - Control – Automation applied in the IAF-AS system**
  - Materials and Methods
  - Results (Dynamic control of biological nitrogen removal processes)
- **Instrumentation - Control – Automation applied in the IAF-MBR system**
  - Materials and Methods
  - Results (Biological and filtration processes control)
- **Conclusions**
- **Novelty**

Introduction

The importance of wastewater treatment

- Environmental problem solution
  - Eutrophication
    - Impact of the human water use
- Wastewater treatment plants (WWTPs) are designed or upgraded for biological nutrient removal (BNR)
- Activated sludge systems:
  - separate anaerobic, anoxic and aerobic reactors
  - single reactors → intermittent aeration

Activated sludge (AS) systems 1/2

Intermittent aeration method

- Applied in the same bioreactor
- Alternate aerobic – anoxic conditions
- Improvement of biological nitrogen removal
- Improvement of effluent quality
- Energy saving (25%)

Intermittent feeding method

- Applied in a short time at the beginning of anoxic phase
- Substrate saturation
- Increase of denitrification rates
- Inhibition of filamentous bacterial growth
- Low SVI

Activated sludge (AS) systems 2/2

Introduction

Organic carbon removal

Aerobic conditions

Heterotrophic biomass

$$COHNS + O_2 \longrightarrow CO_2 + H_2O + NH_3 + C_5H_7NO_2 + energy$$

Nitrogen removal

- Nitrification

  Aerobic conditions

  Autotrophic biomass

$$2NH_4^+ + 3O_2 \xrightarrow{Nitrosomonas} 2NO_2^- + 2H_2O + 4H^+$$

$$2NO_2^- + O_2 \xrightarrow{Nitrobacter} 2NO_3^-$$

- Denitrification

  Anoxic conditions (presence of NO_3^--N)

  Heterotrophic biomass

  Readily biodegradable organic carbon

$$2NO_3^- + 10H^+ + 10e^- \xrightarrow{denitifiers} N_2 + 2OH^- + 4H_2O$$

Advanced AS system: Membrane bioreactor (MBR) systems

Complete removal of suspended solids

High effluent quality

Reclamation and reuse for treated wastewater (JMD 145116/11)

MBR systems can operate at:

- ✓ high loading rates,
- ✓ high MLSS concentration,
- ✓ long SRT,
- ✓ low F/M ratios

Introduction

Membrane bioreactor (MBR) systems

Membrane performance control parameters:

Transmembrane pressure (TMP) $\text{TMP} = P_{feed} - P_{\text{permeate}}$ (bar ή mbar)

Permeate flux (J) $\text{J} = \frac{Q_{out}}{A}$ (L m^{-2} h^{-1})

Membrane permeability (P) $P = \frac{J}{TMP}$ (L m^{-2} h^{-1} bar^{-1})

Resistance (R) $R = \frac{TMP}{J \times n}$ (m^{-1})

Membrane bioreactor (MBR) systems

Classification of MBR control parameters

- Biological process
  - Wastewater feeding
  - Aeration
  - Biomass mixing
  - Biomass recirculation
  - Sludge waste

- Filtration process
  - Permeate flow
  - Backwash flow
  - Air scouring
  - Chemical cleaning

Membrane bioreactor (MBR) systems

MBR system limitation - Membrane fouling

flux decline

higher applied pressures

higher energy consumption

frequent chemical cleaning

Factors affecting membrane fouling

Composition of the wastewater

SRT

F/M ratio

Temperature

Sludge characteristics

↓

Extracellular polymeric substances (EPS) and soluble microbial products (SMP)

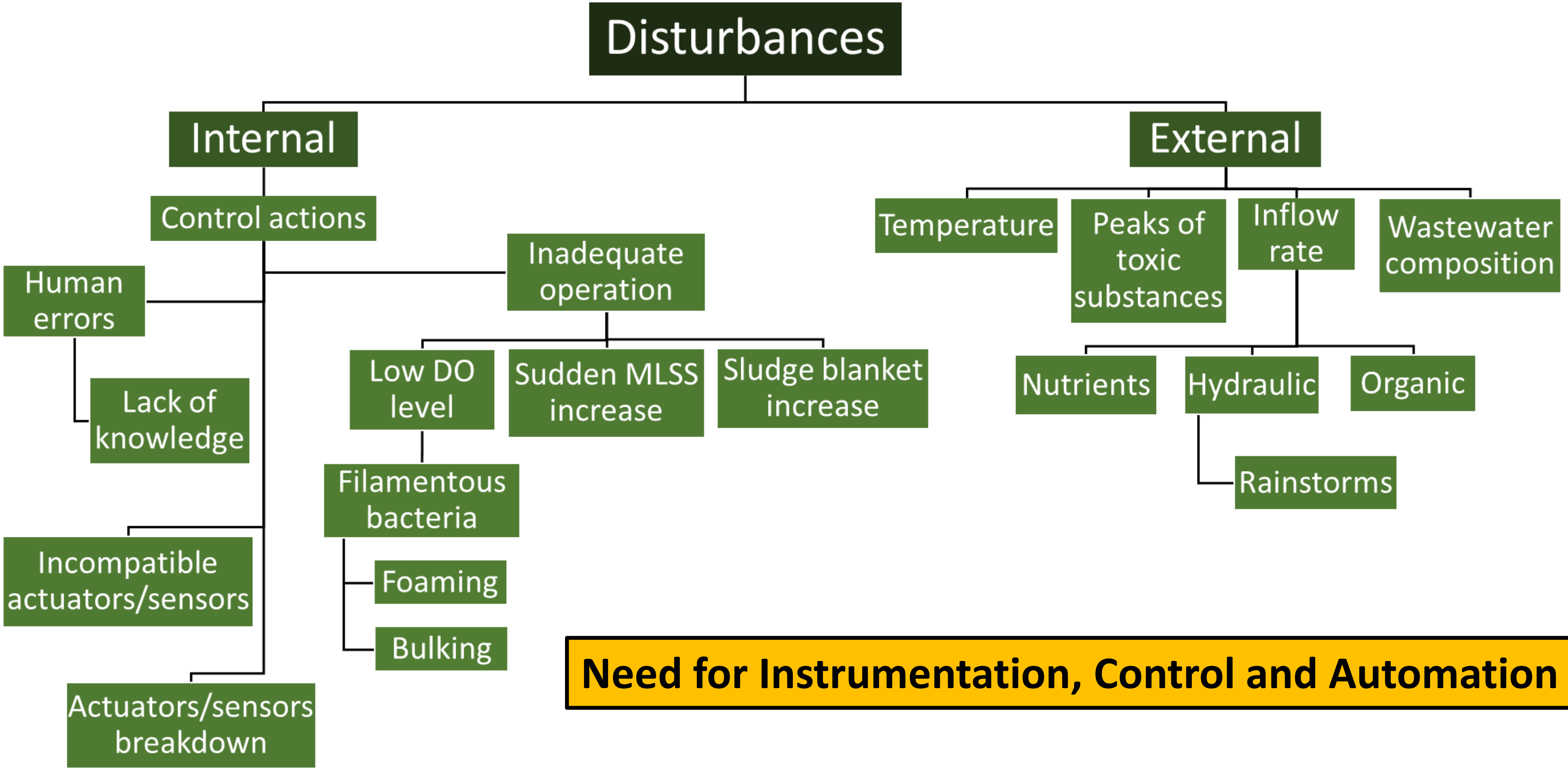
Membrane bioreactor (MBR) systems

MBR system limitation - Membrane fouling classification

- **Reversible** → physical cleaning
- **Irreversible** → chemical cleaning
- **Irrecoverable** → foulants are not removed by any cleaning method

Disturbances in process control of activated sludge systems

Classification of disturbances

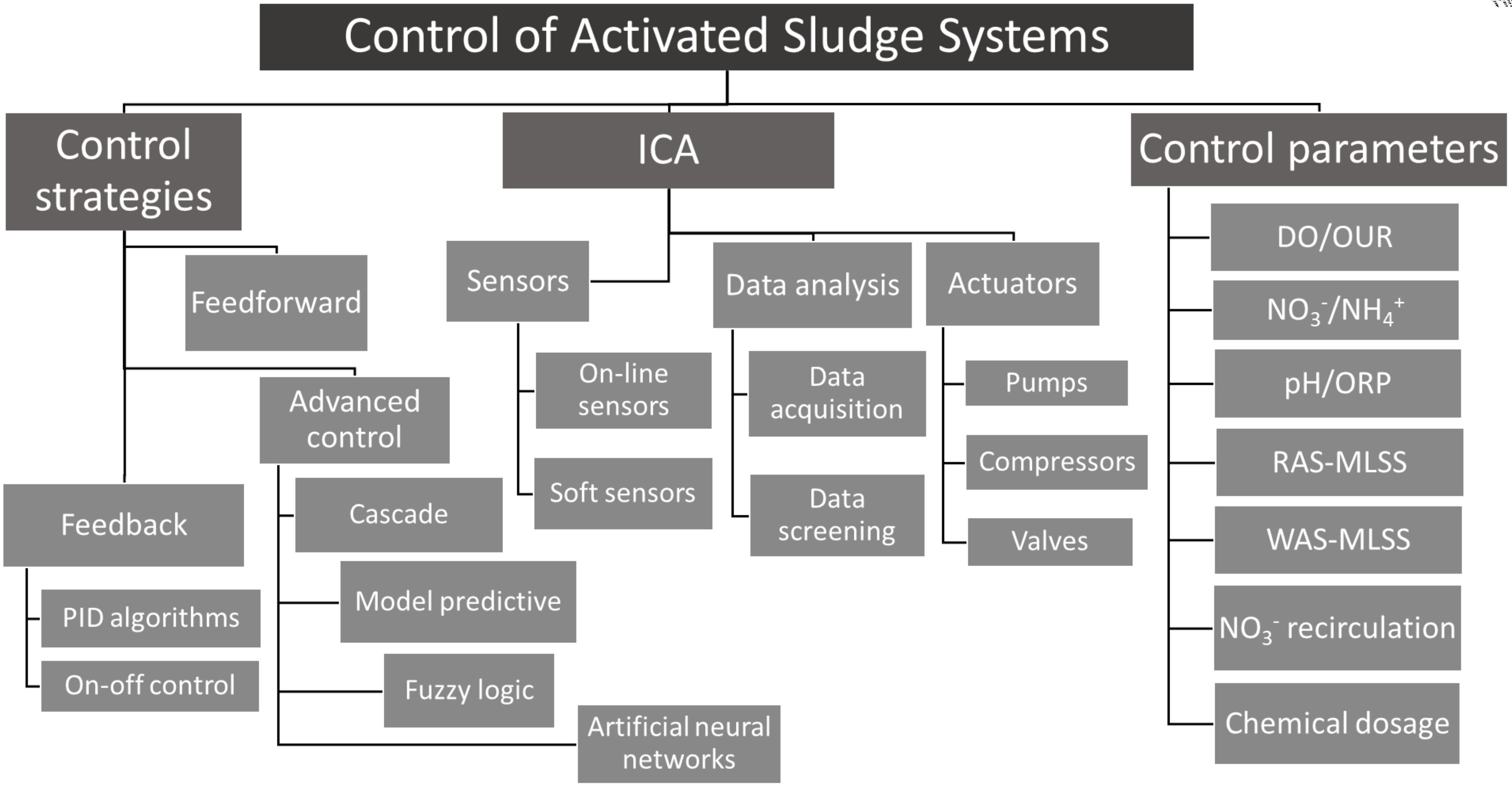


Need for Instrumentation, Control and Automation (ICA)

Instrumentation, Control and Automation (ICA) in WWTPs

- Instrumentation technology, including online nutrient sensors
- Actuators, including variable speed pumps, compressors, stirrers etc.
- Data collection includes data acquisition is available for WWTP supervision and control through software packages
- Computing power
- Advanced dynamical models of many unit processes

Process control in activated sludge systems



Control of Activated Sludge Systems

- Control strategies
  - Feedforward
  - Advanced control
    - Cascade
    - Model predictive
    - Fuzzy logic
    - Artificial neural networks
  - Feedback
    - PID algorithms
    - On-off control
- ICA
  - Sensors
    - On-line sensors
    - Soft sensors
  - Data analysis
    - Data acquisition
    - Data screening
  - Actuators
    - Pumps
    - Compressors
    - Valves
- Control parameters
  - DO/OUR
  - NO_3^-/NH_4^+
  - pH/ORP
  - RAS-MLSS
  - WAS-MLSS
  - NO_3^- recirculation
  - Chemical dosage

Aim and objectives

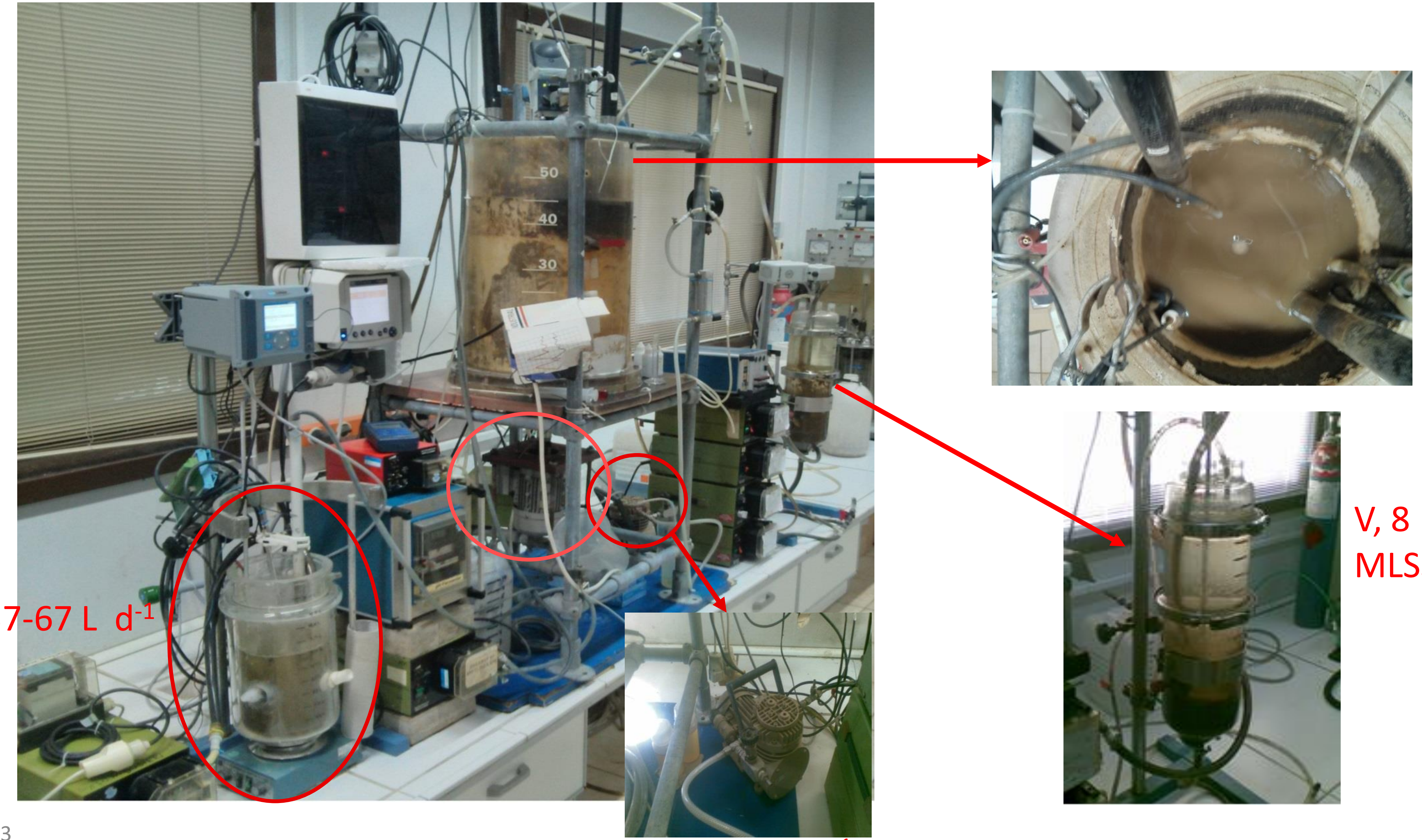
- To implement and assess advanced real-time control strategies of nitrification and denitrification applied in both an intermittently aerated and fed activated sludge system (IAF-AS) and an MBR system (IAF-MBR).
- Process control optimization using *in-situ* sensors:
  - ISE NH_4^+-N and NO_3^+-N,
  - pH,
  - oxidation-reduction potential (ORP),
  - dissolved oxygen (DO),
  - oxygen uptake rate (OUR) biosensor.
- Membrane operation control and filtration performance:
  - a) through online transmembrane pressure (TMP) monitoring
  - b) through EPS and SMP monitoring

NEW APPROACH IN PROCESS CONTROL

Instrumentation - Control - Automation applied in the Intermittently Aerated and Fed Activated Sludge System (IAF-AS) with settling tank

Instrumentation of IAF-AS system with settling tank

Materials and methods



V, 3 L
Q_{inf}, 37-67 L d^{-1}

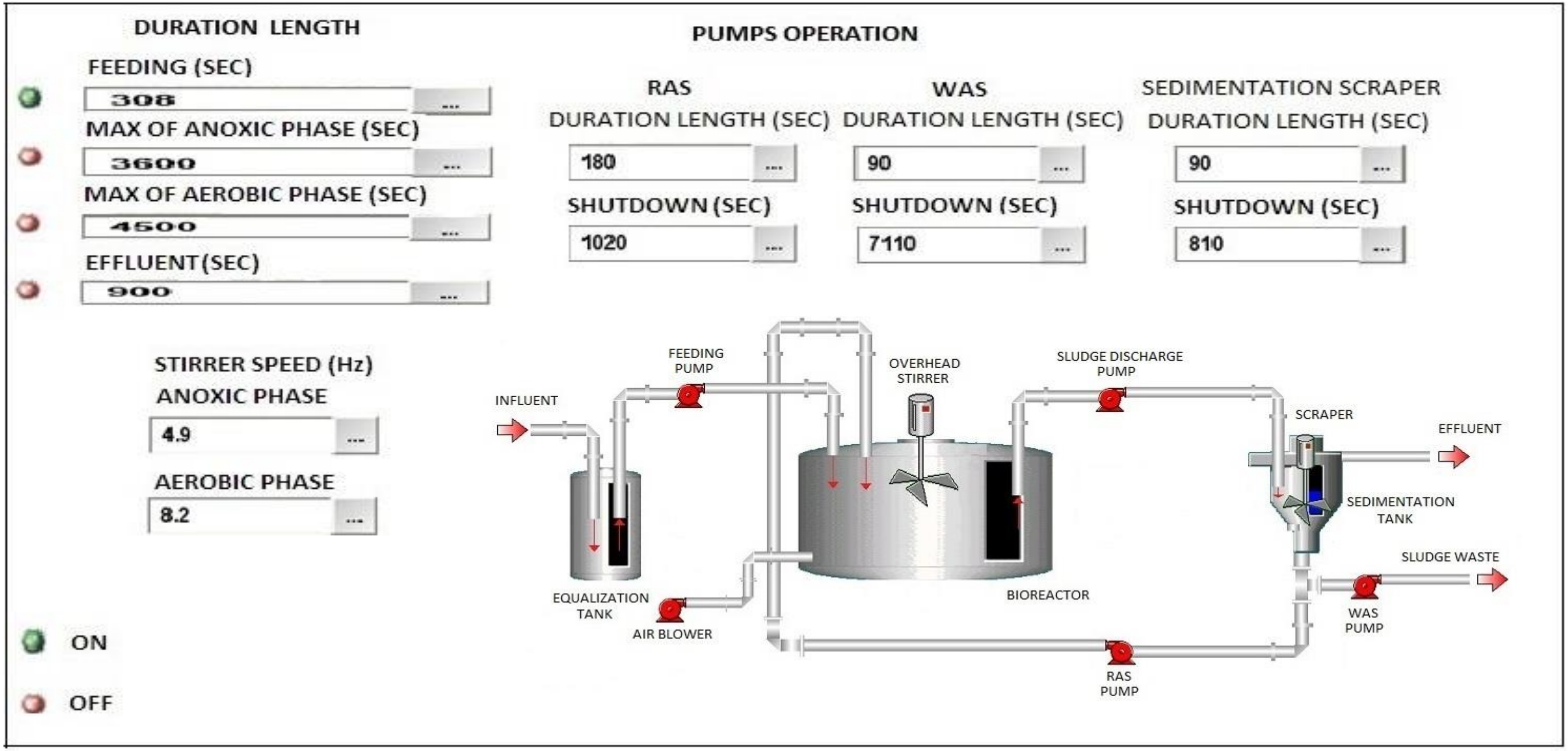
V, 45 L
MLSS, 3 g L^{-1}

V, 8 L
$MLSS_{was}$, 10 g L^{-1}

Q_{air}, 270 L h^{-1}

Graphical user interface to regulate the phases duration and the operation of mechanical apparatus

Materials and methods



DURATION LENGTH

FEEDING (SEC): 308

MAX OF ANOXIC PHASE (SEC): 3600

MAX OF AEROBIC PHASE (SEC): 4500

EFFLUENT (SEC): 900

PUMPS OPERATION

	RAS	WAS	SEDIMENTATION SCRAPER
DURATION LENGTH (SEC)	180	90	90
SHUTDOWN (SEC)	1020	7110	810

STIRRER SPEED (Hz)

ANOXIC PHASE: 4.9

AEROBIC PHASE: 8.2

● ON

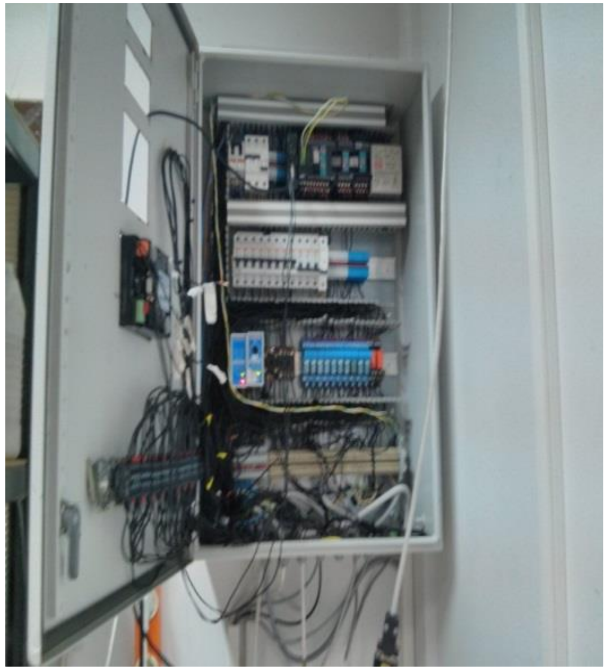
● OFF

Indusoft Web Studio

Materials and methods

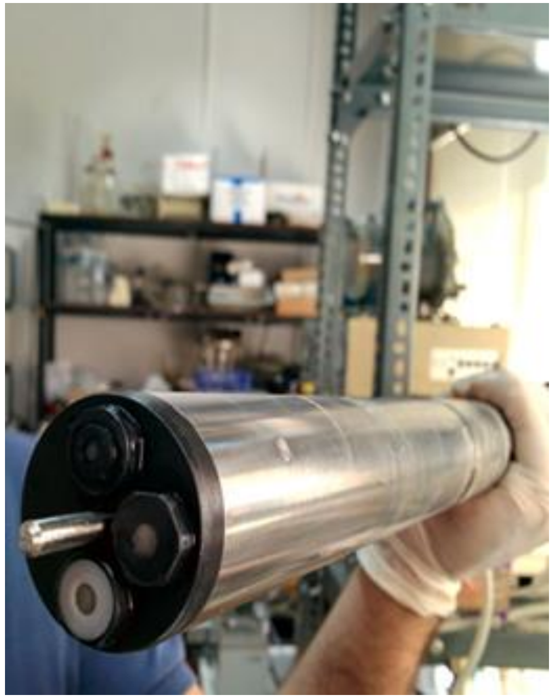
Parts of control system

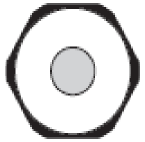
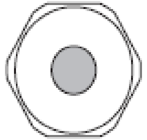
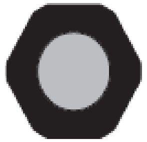
- Programmable Logic Controller (PLC-FATEK FBs-20MC)
- WinProladder V3.21 software package for PLC programming
- Indusoft Web Studio (IWS) software used for SCADA system
- Ion selective electrodes (ISE) VARiON® Plus 700 IQ AmmoLyt® Plus & NitraLyt® Plus

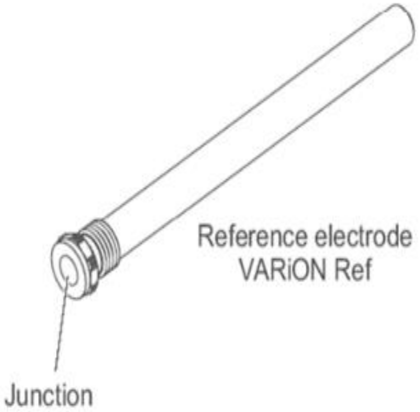


ISE NH_4^+-N and NO_3^--N Sensors

- ❖ need rarely cleaning
- ❖ high measurement accuracy level



Electrode
VARiON® Ref 
VARiON®*Plus* NH4 
VARiON®*Plus* K 
VARiON®Plus NO3 
VARiON®Plus Cl 



Sewage characteristics

Parameters	Average (± St. Deviation)
Total COD (mg L^{-1})	375 ± 72.7
Soluble COD (mg L^{-1})	185 ± 68.9
BOD_5 (mg L^{-1})	230 ± 33.2
NH_4^+-N (mg L^{-1})	57.3 ± 15.8
TKN (mg L^{-1})	73.8 ± 12.9
SS (mg L^{-1})	132 ± 39.1
PO_4^{3+}-P (mg L^{-1})	5.87 ± 1.40
pH	7.67 ± 0.19
EC (μS cm^{-1})	1318 ± 98.9

The domestic wastewater was obtained from University Campus of Xanthi

Materials and methods

Applied real time control strategy

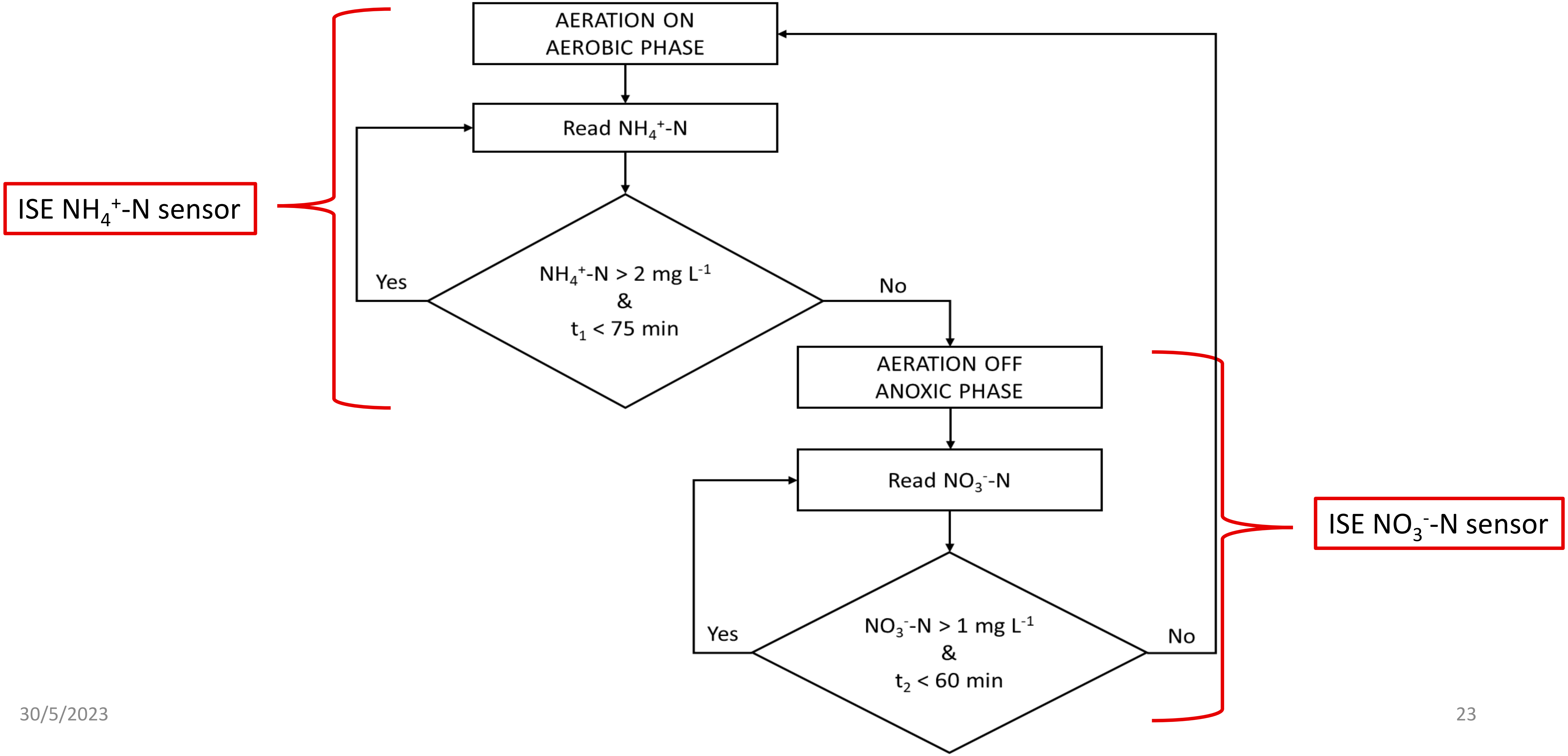
- Feedback control strategy based on rules (set points)
  - Threshold limit NH_4^+-N value: 2 mg L^{-1}
  - Threshold limit NO_3^--N value: 1 mg L^{-1}

- The duration of nitrification and denitrification phases was dynamically regulated depending on nitrogen loading
  - Upper time limit of nitrification: t_1=75 min
  - Upper time limit of denitrification: t_2=60 min

Applied real time control strategy

Materials and methods

Flow chart using *in-situ* online NH_4^+-N and NO_3^--N ISE sensors



ISE NH_4^+-N sensor

AERATION ON
AEROBIC PHASE

Read NH_4^+-N

NH_4^+-N > 2 mg L^{-1}
&
$t_1 < 75$ min

Yes

No

AERATION OFF
ANOXIC PHASE

Read NO_3^--N

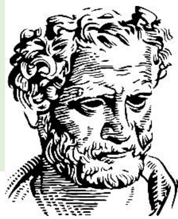
NO_3^--N > 1 mg L^{-1}
&
$t_2 < 60$ min

Yes

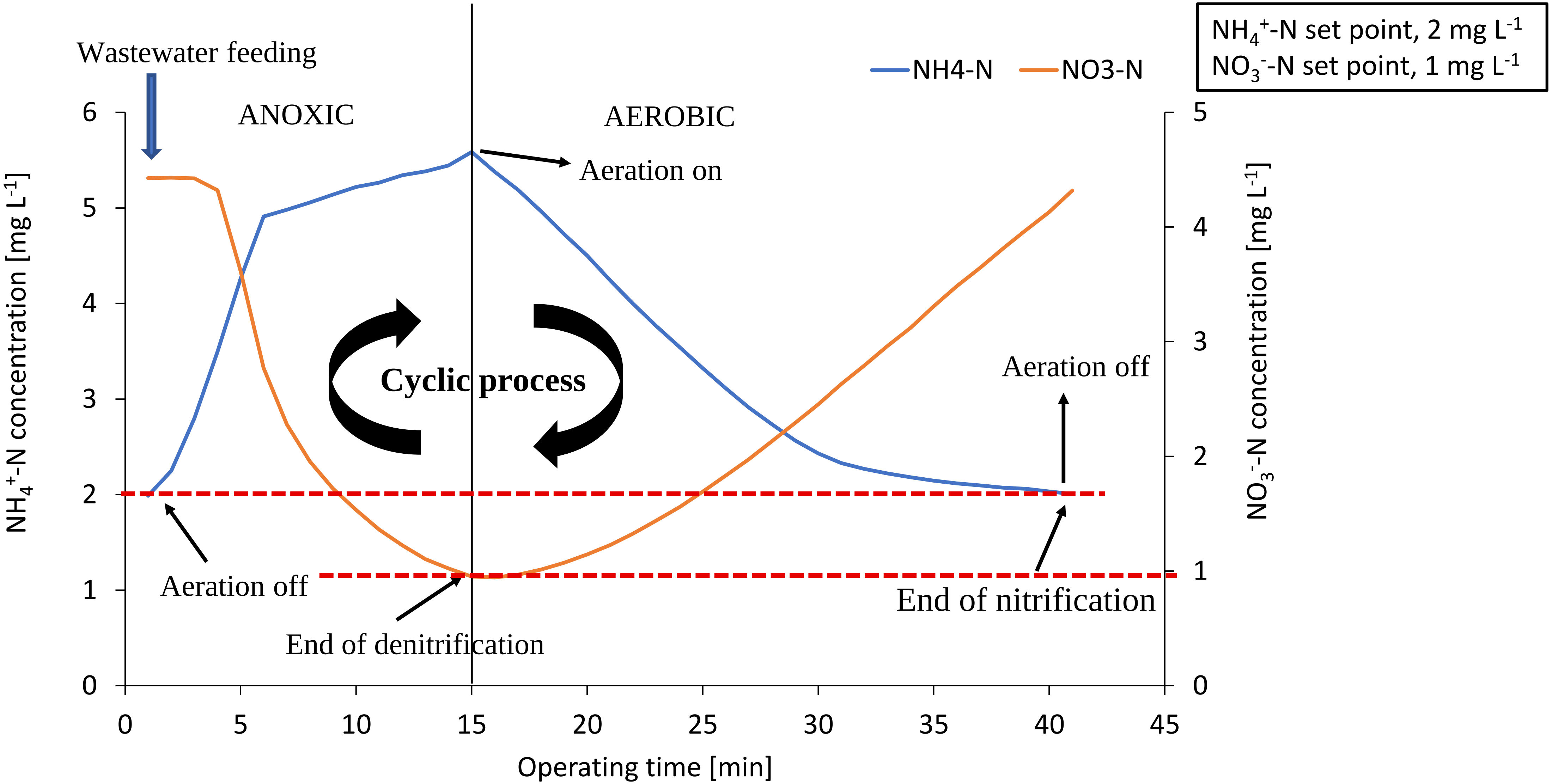
No

ISE NO_3^--N sensor

Alternating anoxic/aerobic cyclic process control during an operational cycle



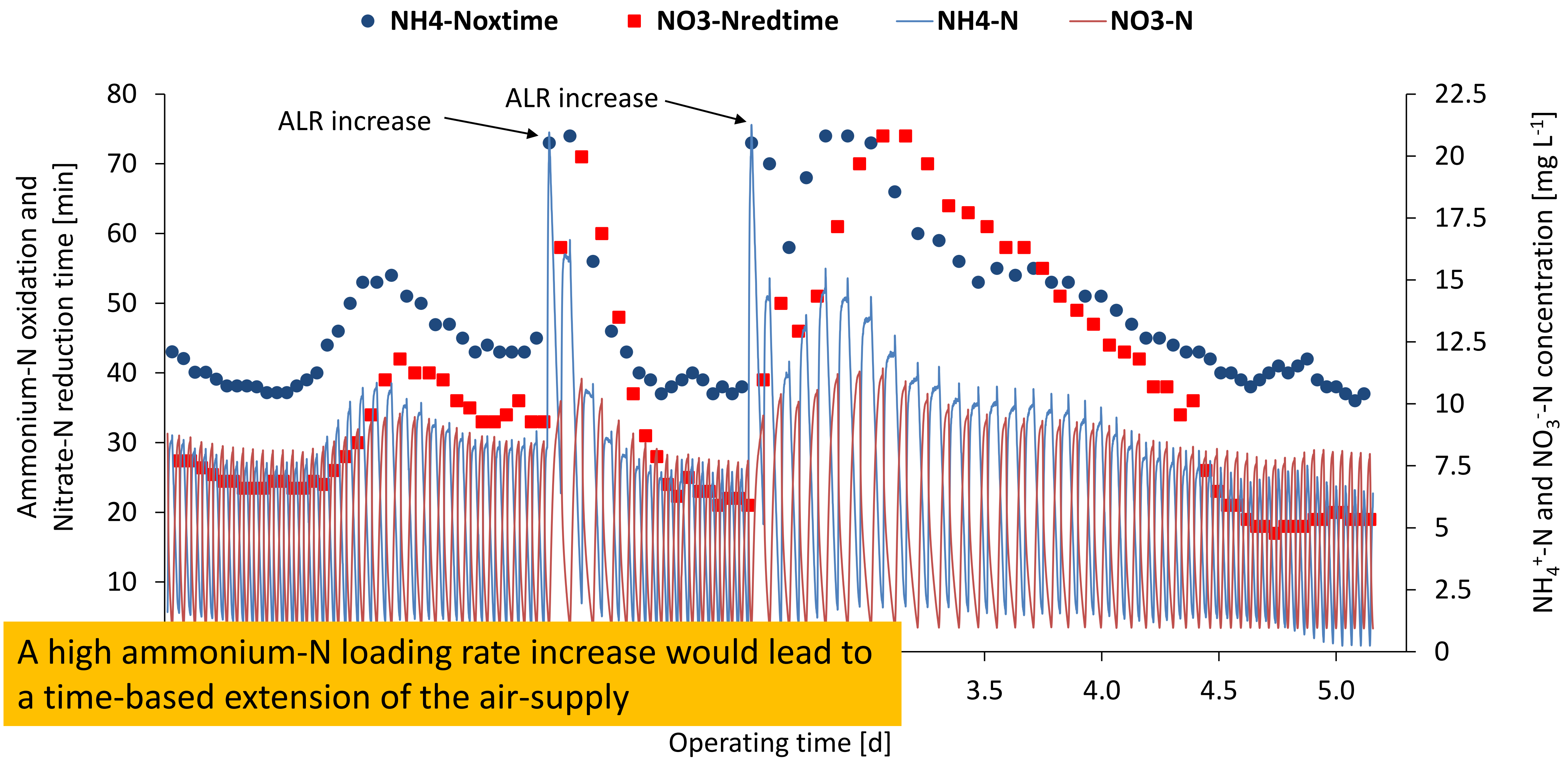
Results



NH_4^+-N set point, 2 mg L^{-1}
NO_3^--N set point, 1 mg L^{-1}

NH_4^+-N and NO_3^--N profiles with respective N-reaction time

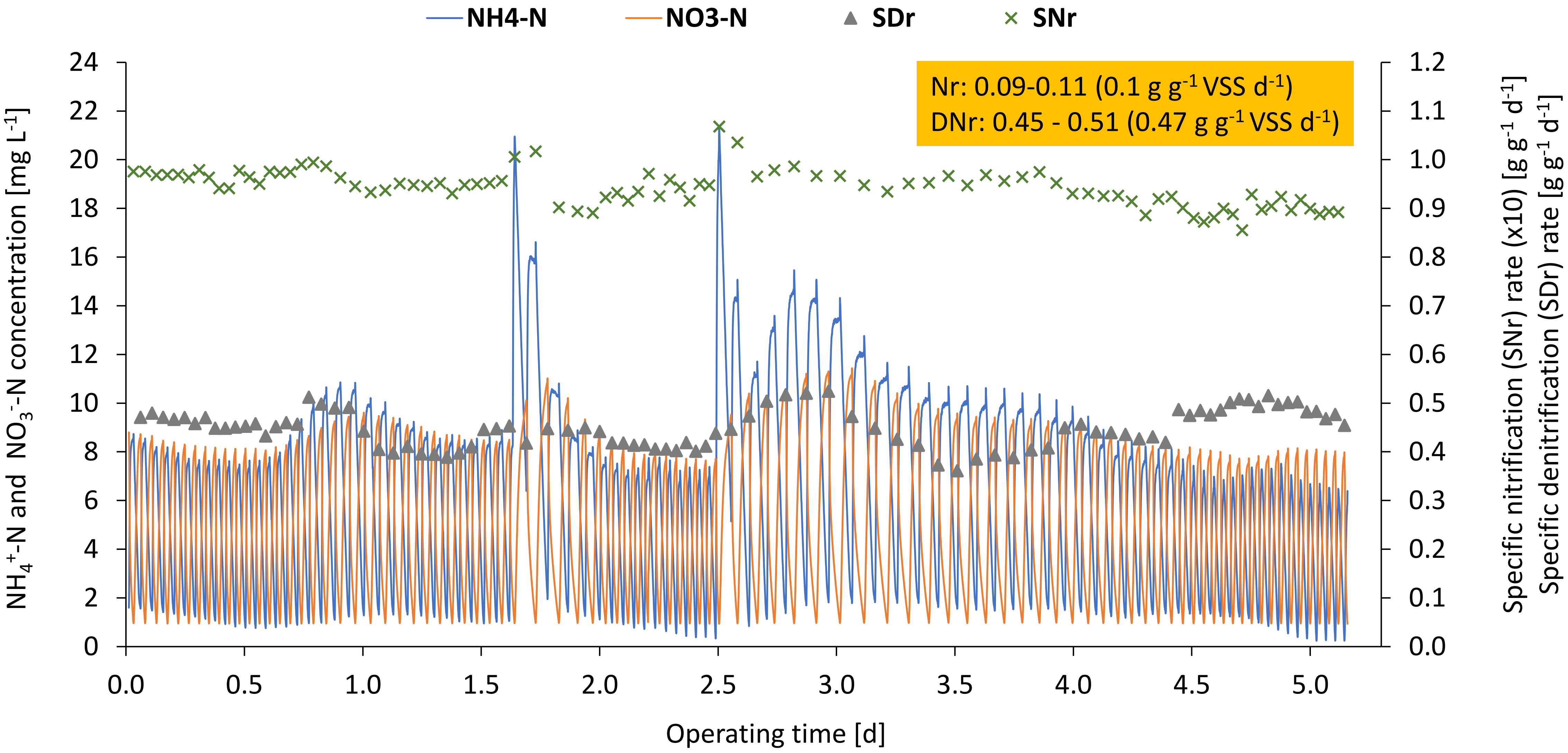
Results



A high ammonium-N loading rate increase would lead to a time-based extension of the air-supply

Results

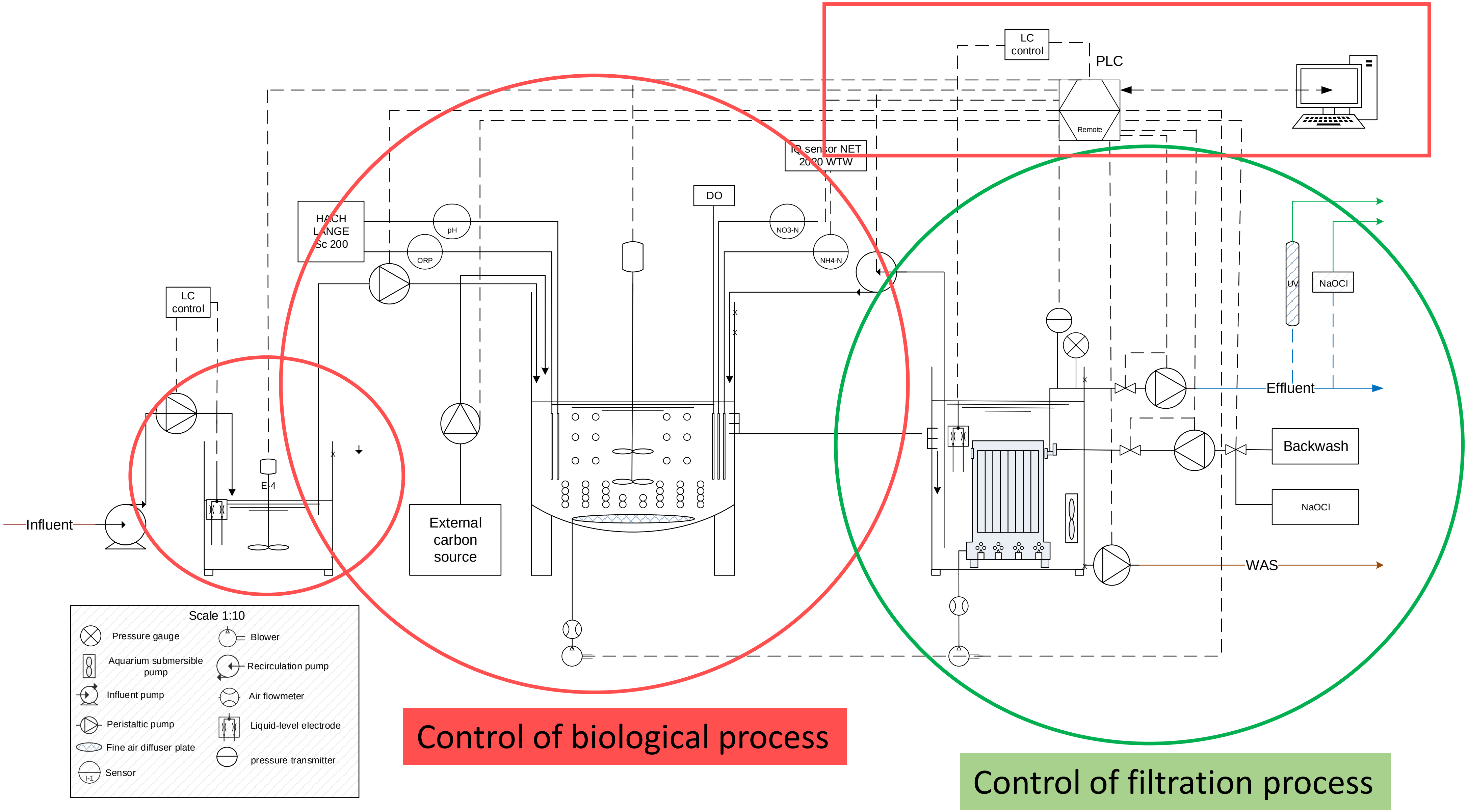
Fluctuation of specific nitrification (SNr) and denitrification rates (SDNr) at NH_4^+-N and NO_3^--N profiles



NEW APPROACHES IN ADVANCED PROCESS CONTROL

Instrumentation - Control - Automation applied in the Intermittently Aerated and Fed MBR system

Schematic design of the pilot-scale external submerged MBR system

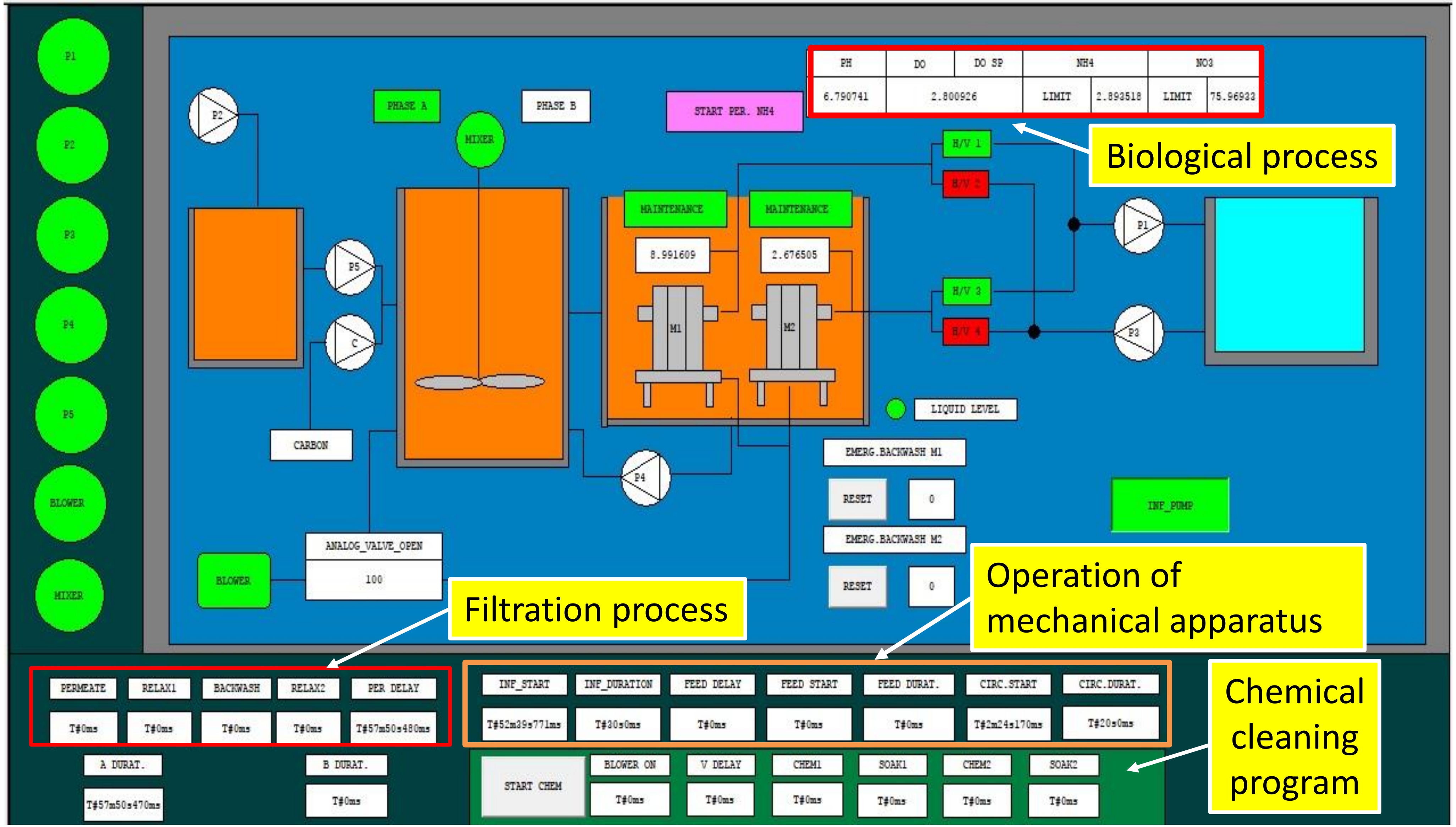


Control of biological process

Control of filtration process

Graphical user interface of the IAF-MBR system

Materials and methods



PH	DO	DO SP	NH4		NO3	
6.790741	2.800926		LIMIT	2.893518	LIMIT	75.96933

EMERG.BACKWASH M1	
RESET	0

EMERG.BACKWASH M2	
RESET	0

PERMEATE	RELAX1	BACKWASH	RELAX2	PER DELAY
T#0ms	T#0ms	T#0ms	T#0ms	T#57m50s480ms

A DURAT.	B DURAT.
T#57m50s470ms	T#0ms

INF_START	INF_DURATION	FEED DELAY	FEED START	FEED DURAT.	CIRC.START	CIRC.DURAT.
T#52m39s771ms	T#30s0ms	T#0ms	T#0ms	T#0ms	T#2m24s170ms	T#20s0ms

START CHEM	BLOWER ON	V DELAY	CHEM1	SOAK1	CHEM2	SOAK2
	T#0ms	T#0ms	T#0ms	T#0ms	T#0ms	T#0ms

Biological process

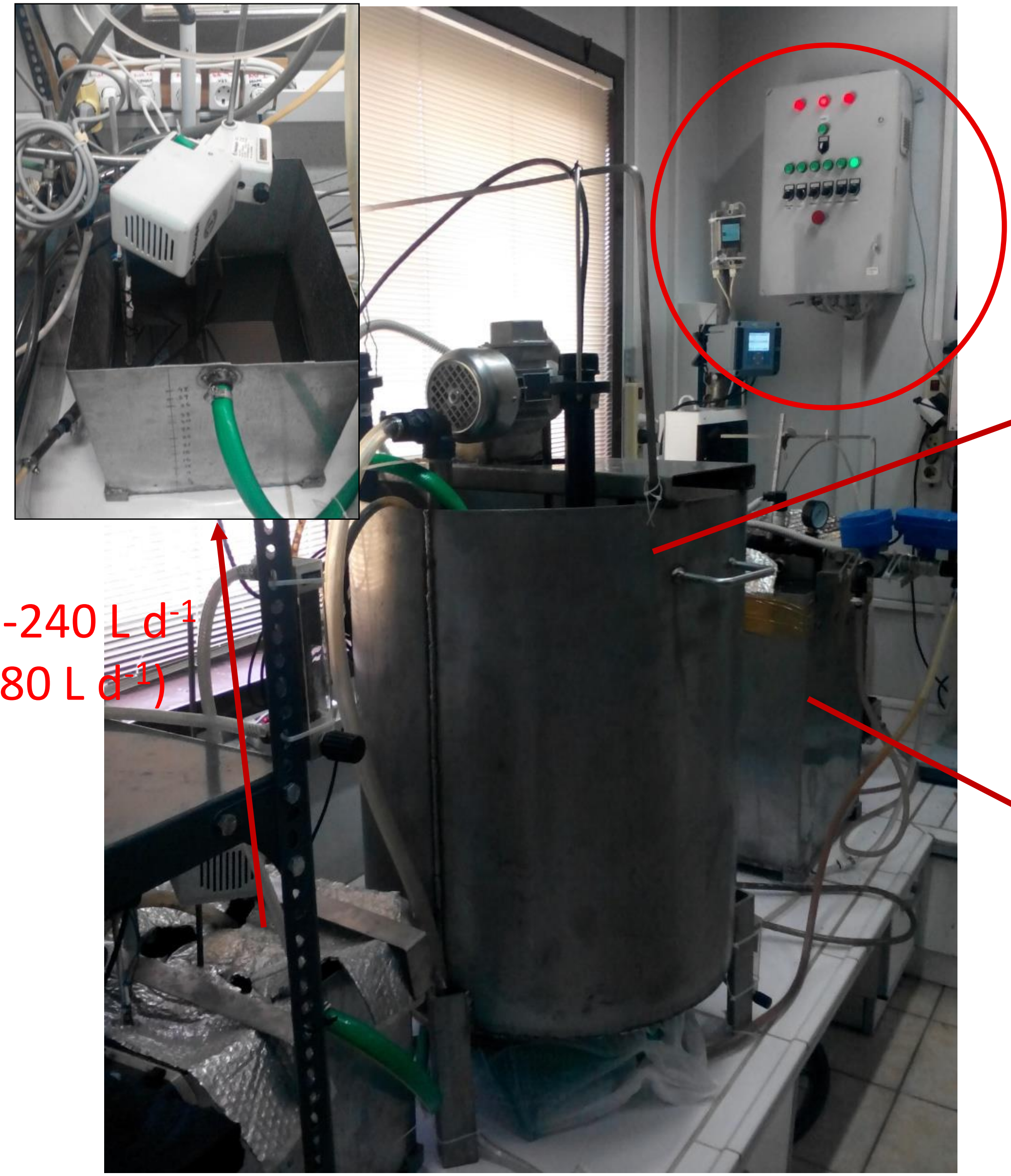
Filtration process

Operation of mechanical apparatus

Chemical cleaning program

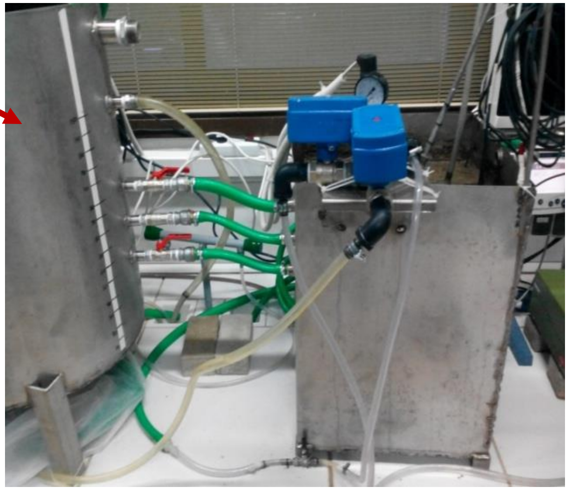
CODESYS software

Instrumentation of the IAF-MBR system



V, 40 L
Q_{inf}, 96-240 L d^{-1}
(Avg, 180 L d^{-1})

V, 100 L
MLSS ≤ 9 g L^{-1}



V, 80 L
MLSS ≤ 9 g L^{-1}
UF membranes

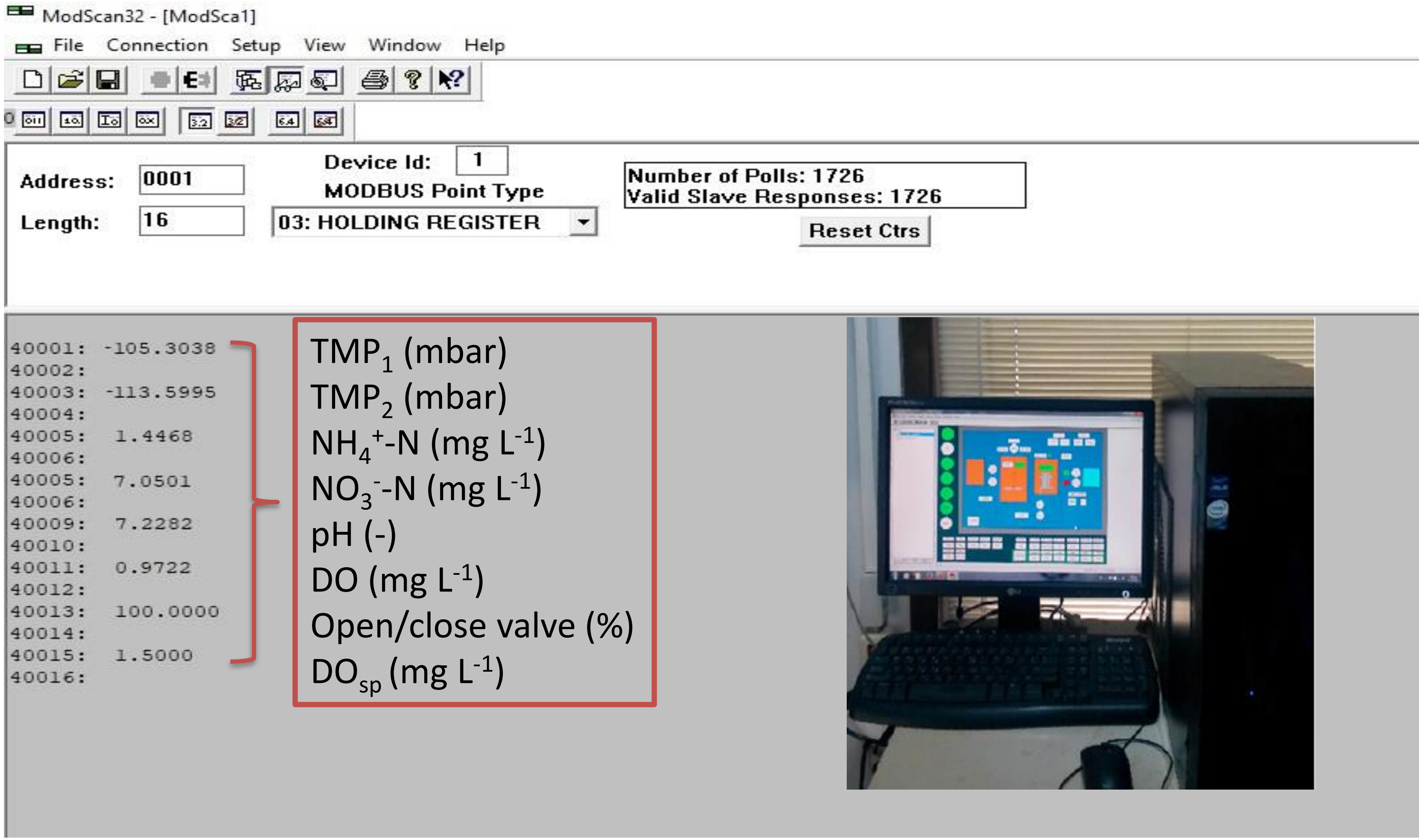
Parts of control system

Materials and methods

- ABB’s Programmable Logic Controller PLC (ac500 echo PM564)
- Controller Functionality Software (CODESYS)
- HACH LANGE & IQ2020XT WTW Controller
- HACH LANGE ORP and pH GmbH sensors
- Optical WTW FDO 700 IQ sensor

Recording data through Modsca32 software

Materials and methods



Address: 0001

Length: 16

Device Id: 1

MODBUS Point Type: 03: HOLDING REGISTER

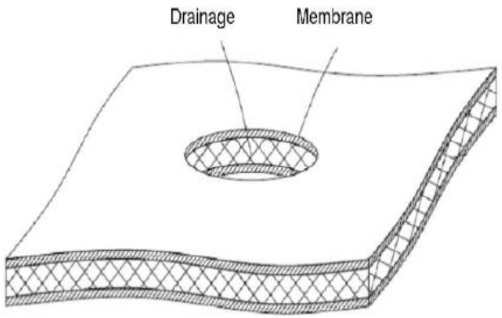
Number of Polls: 1726
Valid Slave Responses: 1726

```
40001:  -105.3038
40002:
40003:  -113.5995
40004:
40005:    1.4468
40006:
40005:    7.0501
40006:
40009:    7.2282
40010:
40011:    0.9722
40012:
40013:  100.0000
40014:
40015:    1.5000
40016:
```

- TMP_1 (mbar)
- TMP_2 (mbar)
- NH_4^+-N (mg L^{-1})
- NO_3^--N (mg L^{-1})
- pH (-)
- DO (mg L^{-1})
- Open/close valve (%)
- DO_{sp} (mg L^{-1})

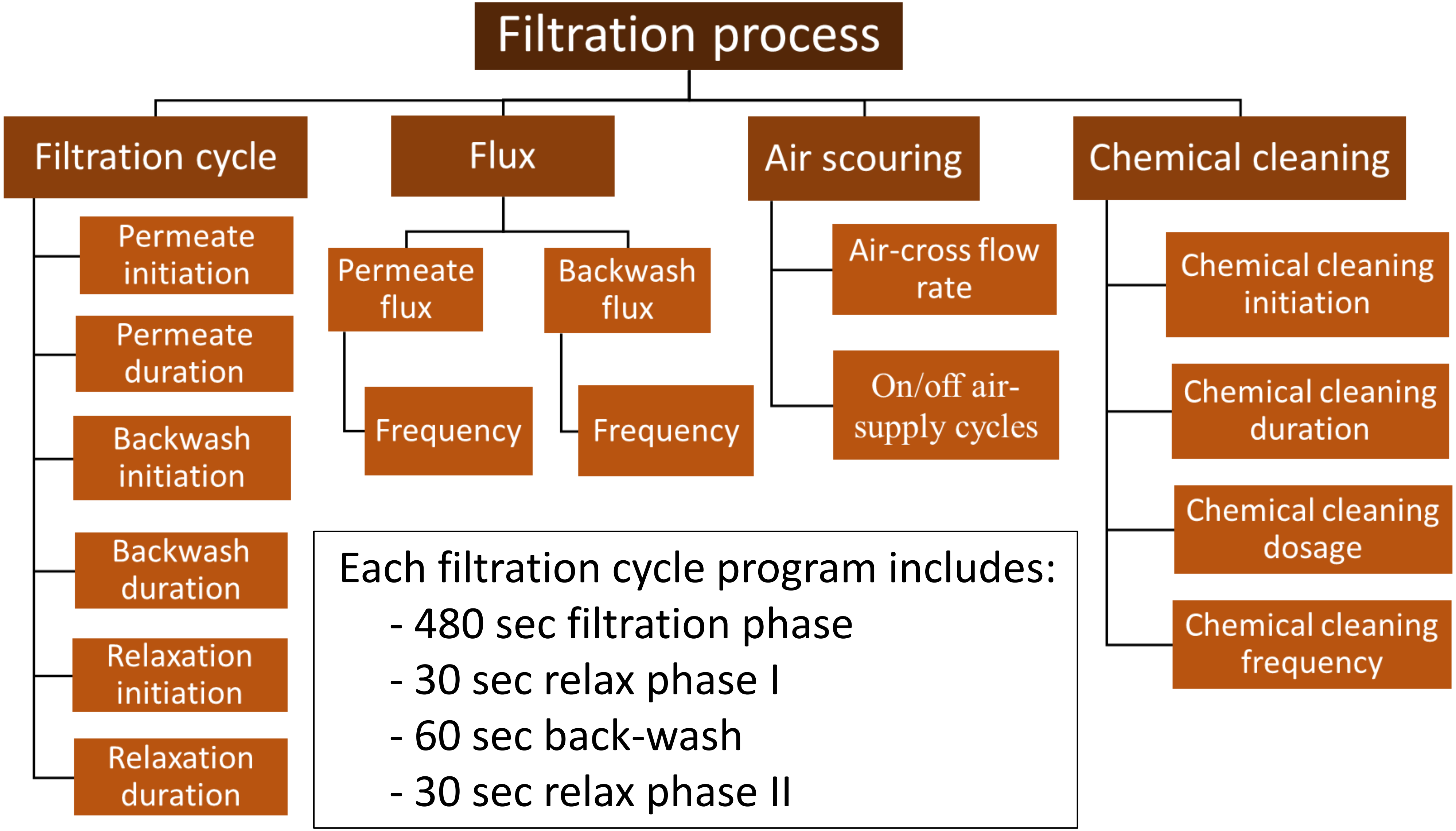
Characteristics of the ultrafiltration membrane module

Membrane type	Flat sheet (Microdyn Nadir) (UP-150)	Pore size	0.04 µm
Construction material	Hydrophilic polyether-sulfone	Effective filtration area	0.34 m^2
Maximum operating pressure during filtration	-400 mbar	Maximum operating backwash pressure	+150 mbar



Filtration process control

Categorization of control parameters for filtration process control



- Filtration process
  - Filtration cycle
    - Permeate initiation
    - Permeate duration
    - Backwash initiation
    - Backwash duration
    - Relaxation initiation
    - Relaxation duration
  - Flux
    - Permeate flux
      - Frequency
    - Backwash flux
      - Frequency
  - Air scouring
    - Air-cross flow rate
    - On/off air-supply cycles
  - Chemical cleaning
    - Chemical cleaning initiation
    - Chemical cleaning duration
    - Chemical cleaning dosage
    - Chemical cleaning frequency

Each filtration cycle program includes:

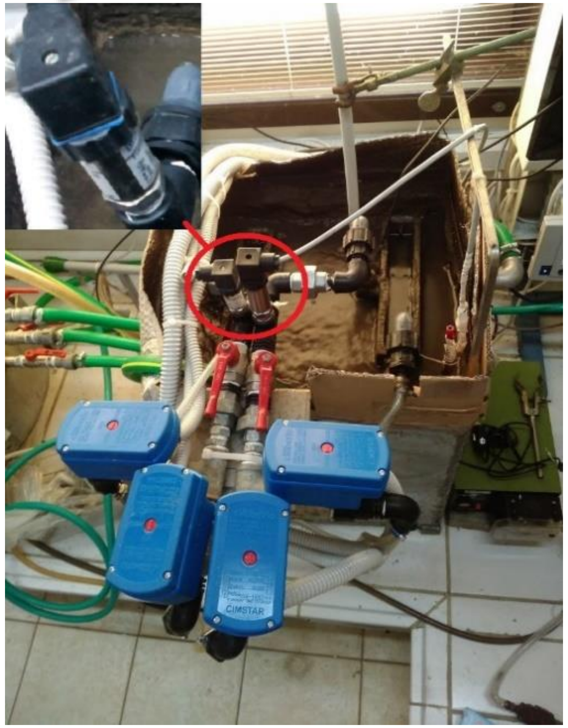
- 480 sec filtration phase
- 30 sec relax phase I
- 60 sec back-wash
- 30 sec relax phase II

Materials and methods

TMP monitoring and control

- The recording TMP data were online logged (every minute)
- Filtration limit TMP -300 mbar
- If TMP ≥ -300 mbar filtration was stopped (membrane fouling)
- Emergency backwash
- If TMP recording ≥ -300 mbar backwash was replicated (Backwash limit TMP < 150 mbar)

Pressure transmitter



If TMP remains greater than -300 mbar, membrane cleaning was initiated

Membrane cleaning methods

- **Physical cleaning is applied to remove reversible fouling**

  Methods
  - ✓ Backflushing (frequency/volume increase)
  - ✓ Air flow velocity increase

- **Mechanical cleaning is referred to:**

  Method
  - ✓ sweeping (sponge)

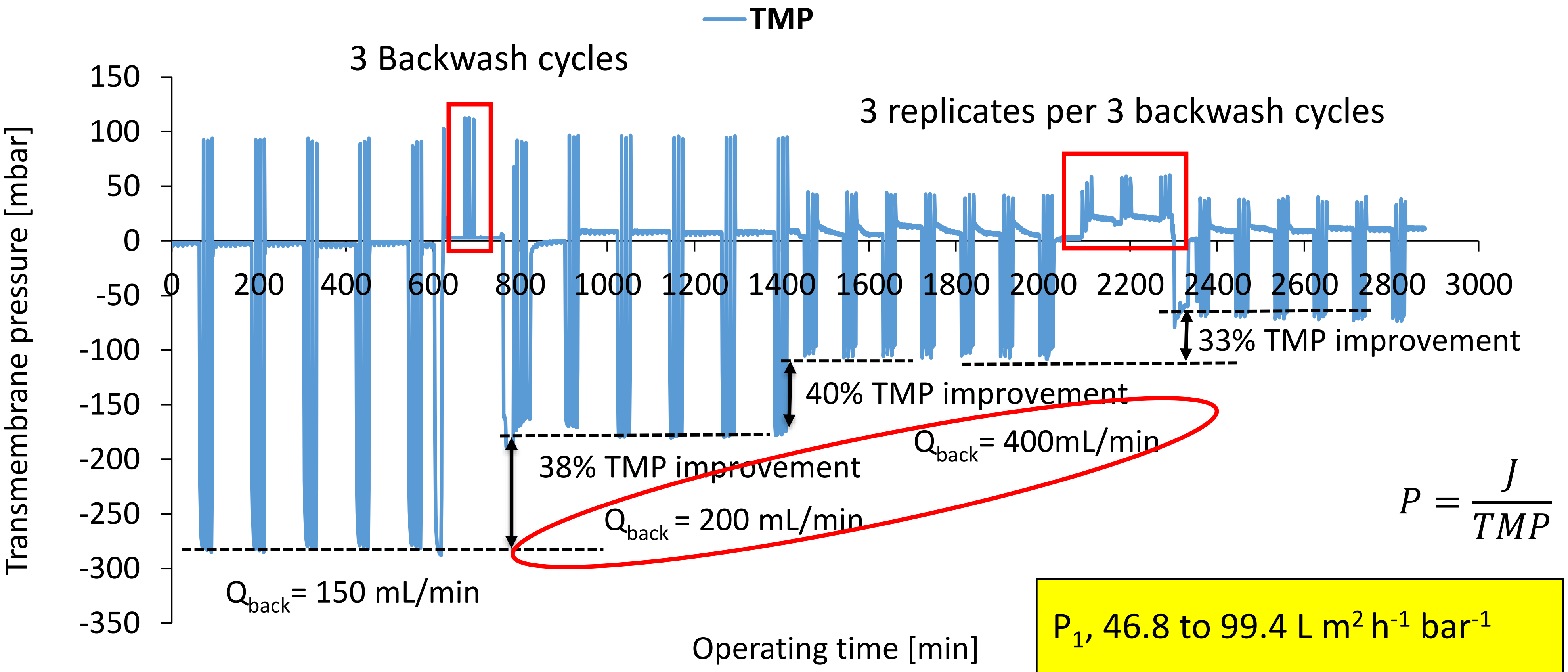
- **Chemical cleaning is applied to remove irreversible fouling**

  Methods
  - ✓ *In-situ* (automated cleaning method) – *ex-situ* (intensive cleaning method)
  - ✓ Use of citric acid (0,2% w/v) and NaOCl (100-1000 ppm)

TMP profile after physical cleaning

Results

Gradual backwash volume increase and successive backflushing applications



$$P = \frac{J}{TMP}$$

P_1, 46.8 to 99.4 L m^2 h^{-1} bar^{-1}

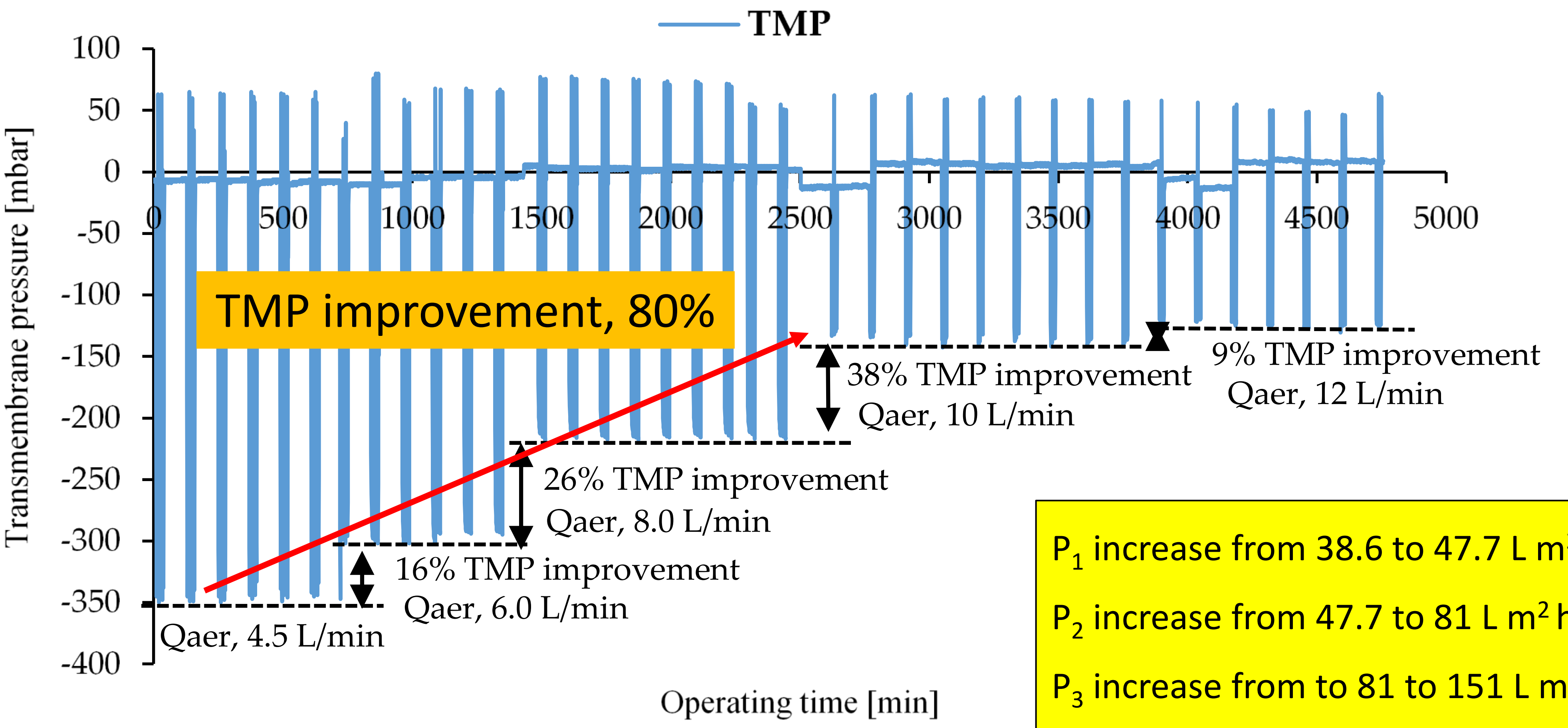
P_2, 99.4 to 126 L m^2 h^{-1} bar^{-1}

P_3, 126 to 221 L m^2 h^{-1} bar^{-1}

TMP profile after physical cleaning

TMP profile under various aeration velocities for air scouring

Results



$$P = \frac{J}{TMP}$$

P_1 increase from 38.6 to 47.7 L m^2 h^{-1} bar^{-1}

P_2 increase from 47.7 to 81 L m^2 h^{-1} bar^{-1}

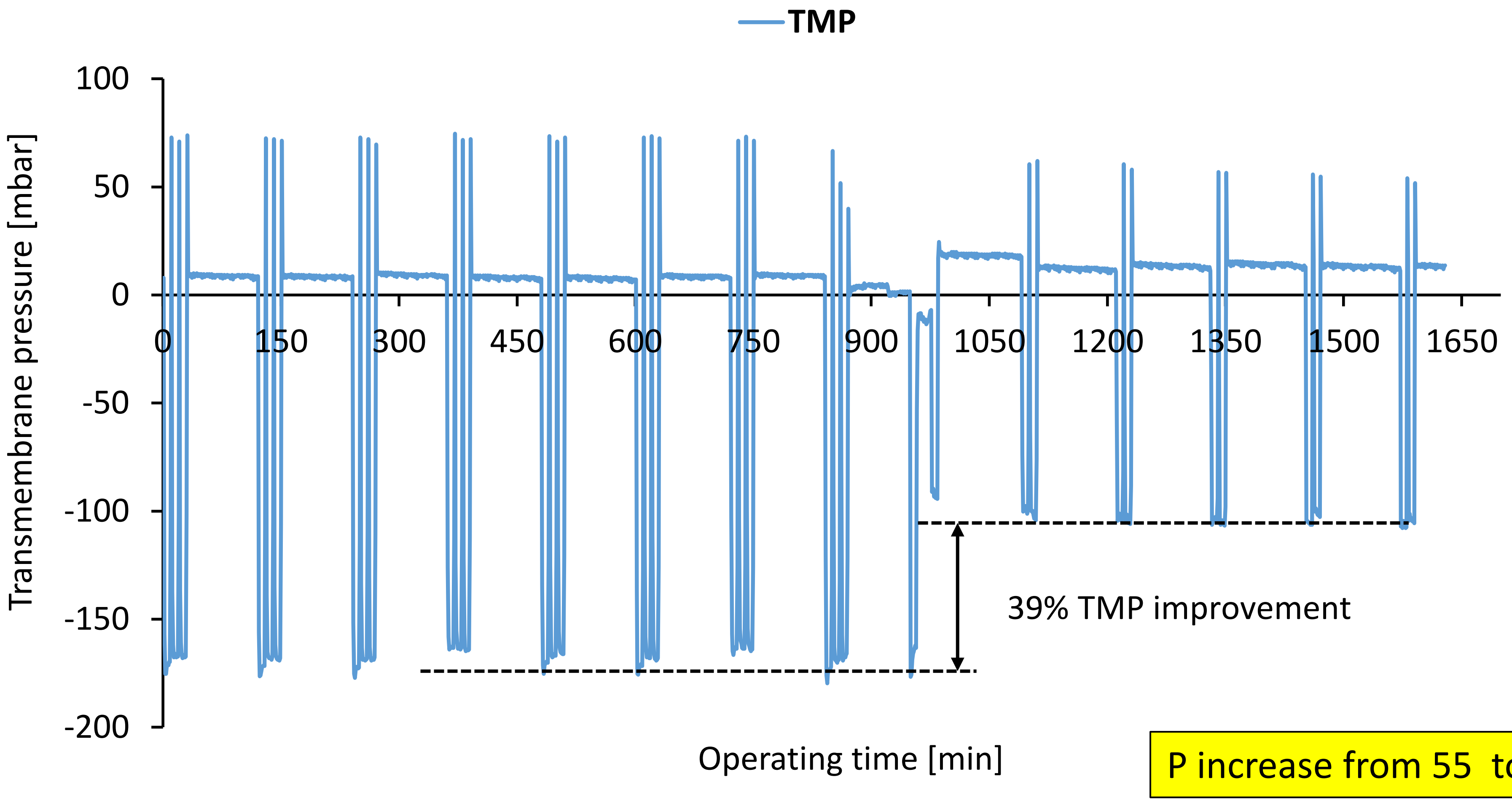
P_3 increase from to 81 to 151 L m^2 h^{-1} bar^{-1}

P_4 increase from 151 to 181 L m^2 h^{-1} bar^{-1}

TMP profile after mechanical cleaning

Results

TMP profile after *in-situ* membrane layer scrapping



$$P = \frac{J}{TMP}$$

P increase from 55 to 245 L m^{-2} h^{-1} bar^{-1}

TMP profiles after chemical cleaning

Results

$$P = \frac{J}{TMP}$$

P increase from 123 to 404 L m^{-2} h^{-1} bar^{-1}

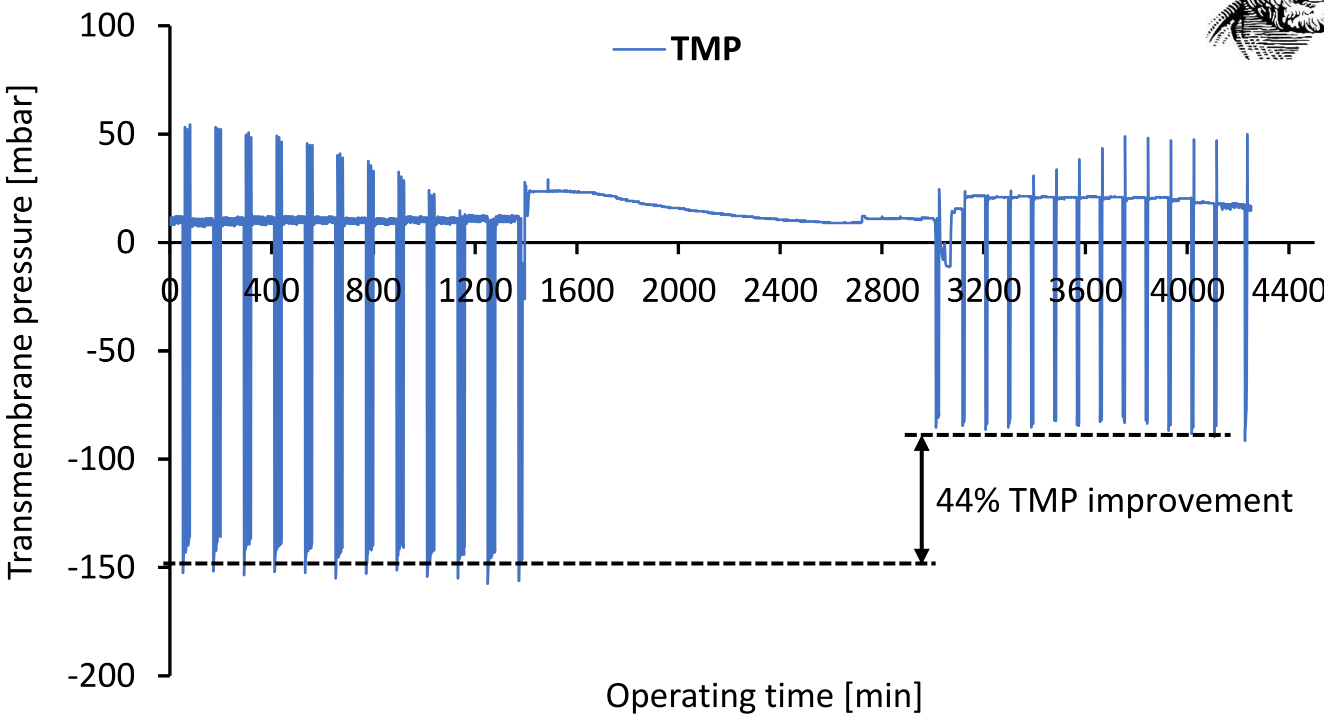


Fig. 1. Ex-situ chemical cleaning with 750 ppm NaOCl solution.

P increase from 36 to 180 L m^{-2} h^{-1} bar^{-1}

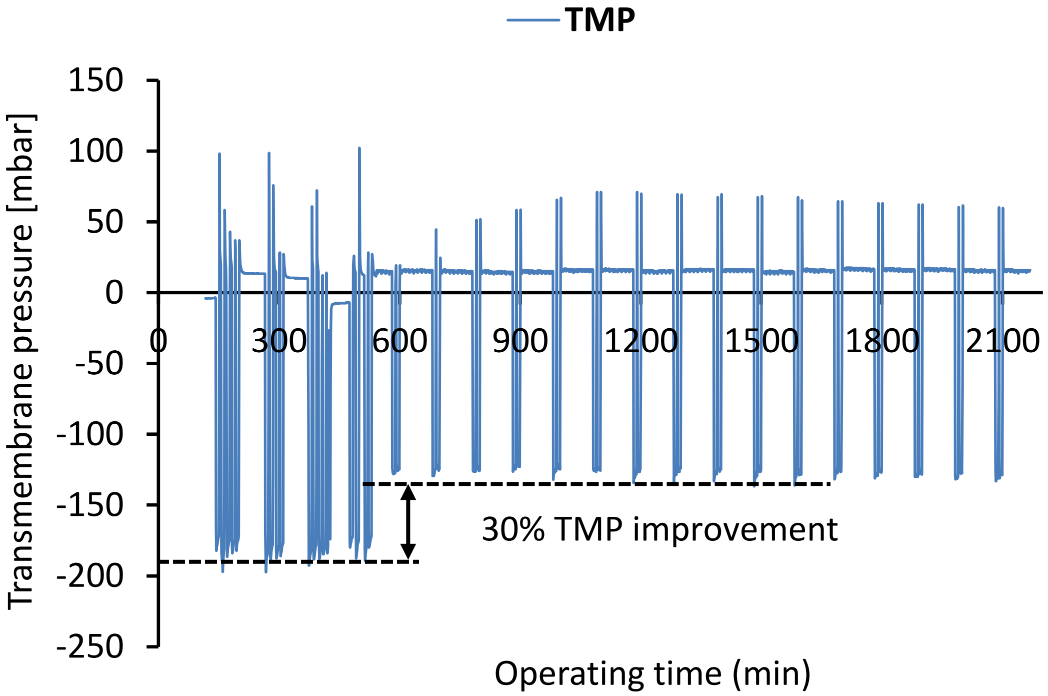


Fig. 2. Ex-situ chemical cleaning with 0.2 w/v citric acid solution.

$$P = \frac{J}{TMP}$$

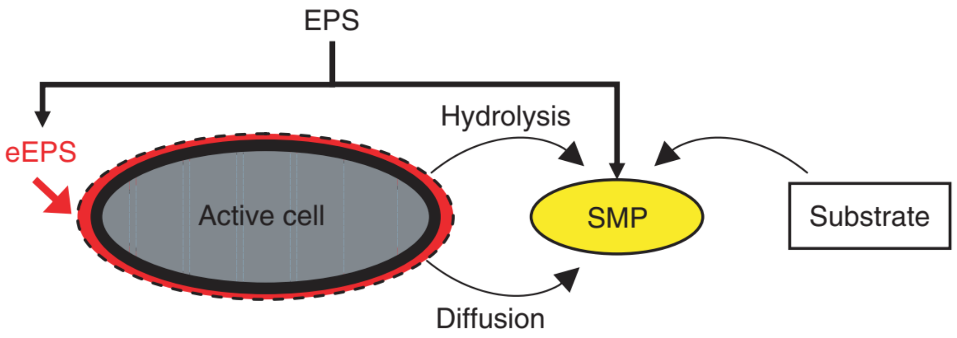
Fouling prevention methods

Fouling prevention methods (membrane remains clean for extended time)

- Intermittent aeration (anoxic/aerobic phase duration ratios)
- Filtration process below critical flux

Evaluation of the main factors affecting membrane fouling

- Extracellular polymeric substances (EPS) and
- Soluble microbial products (SMP)



✓ produced by bacteria

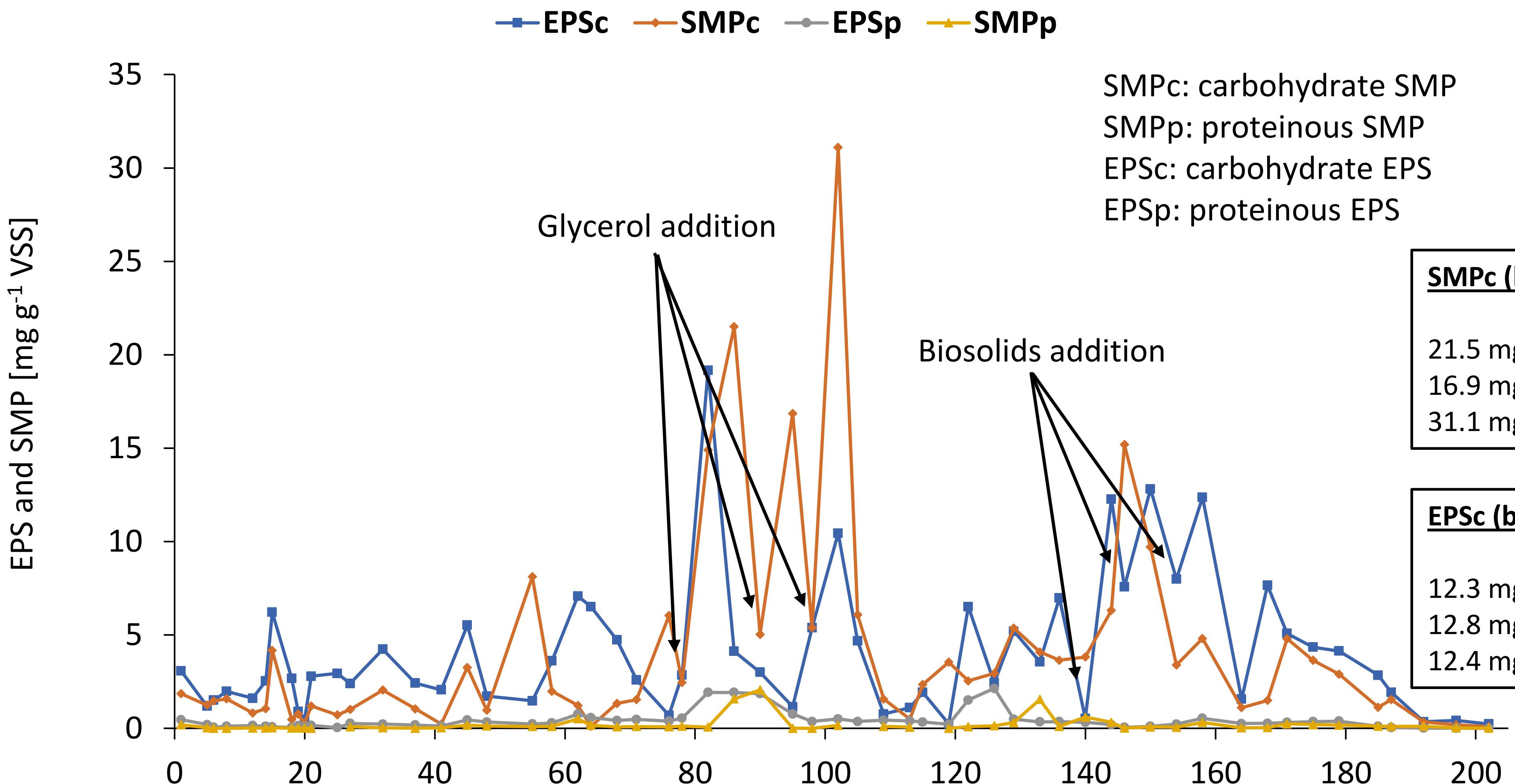
✓ fouling propensity monitoring

✓ Strong impact on EPS and SMP level:

↓

Composition of wastewater- F/M ratio

EPS and SMP concentration profiles



SMPc: carbohydrate SMP
SMPp: proteinous SMP
EPSc: carbohydrate EPS
EPSp: proteinous EPS

SMPc (by glycerol addition):

21.5 mg g^{-1} VSS (day 86)
16.9 mg g^{-1} VSS (day 95)
31.1 mg g^{-1} VSS (day 102)

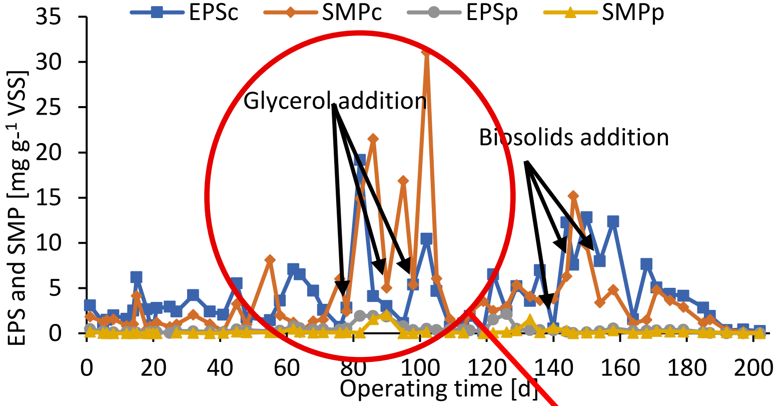
EPSc (by biosolids addition):

12.3 mg g^{-1} VSS (day 144)
12.8 mg g^{-1} VSS (day 146)
12.4 mg g^{-1} VSS (day 154)

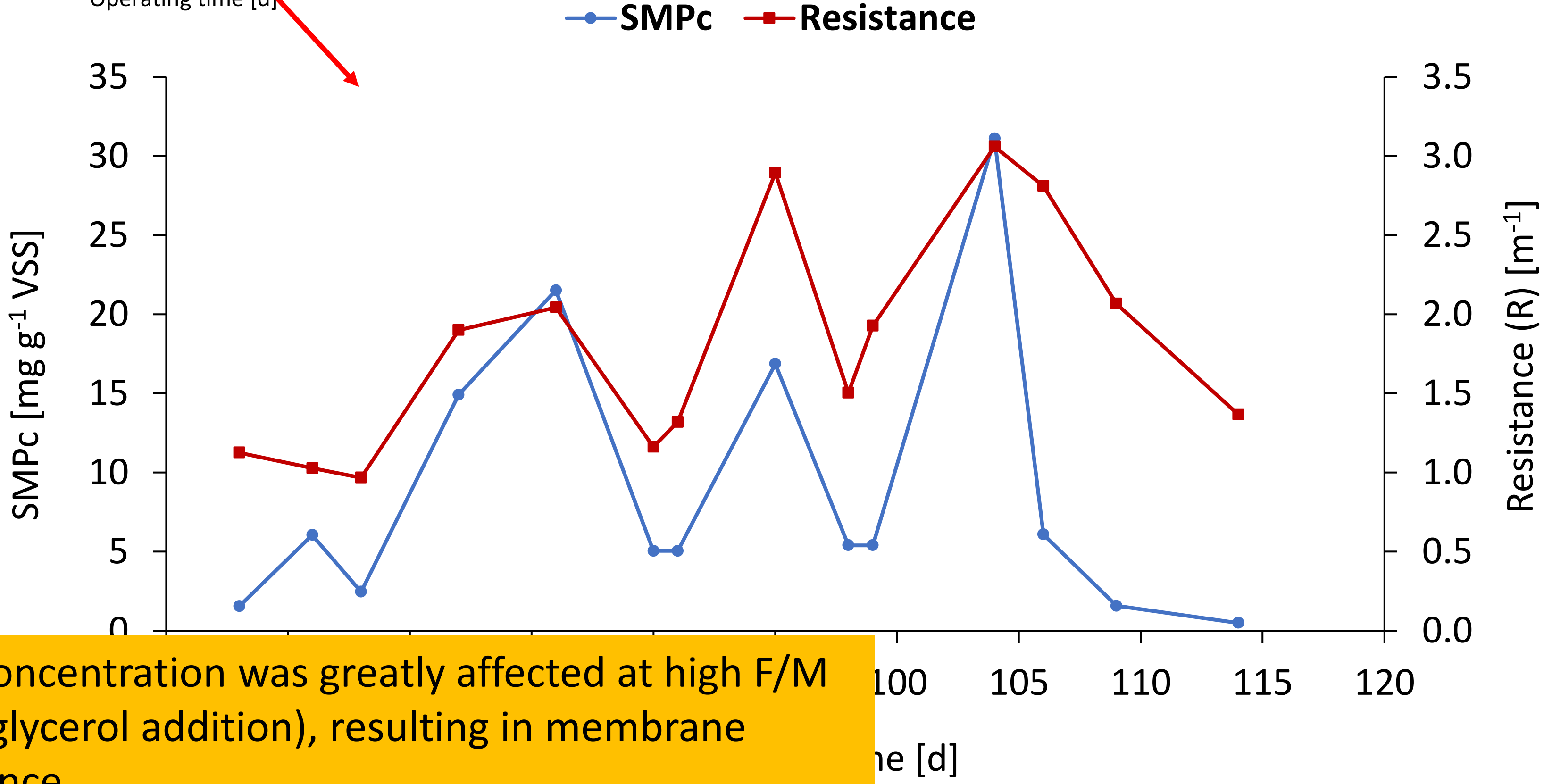
The production of EPS and SMP was low, due to the fact that the influent COD was used for energy production and to a lesser extent for cell synthesis.

Correlation between SMPc and membrane resistance

Results



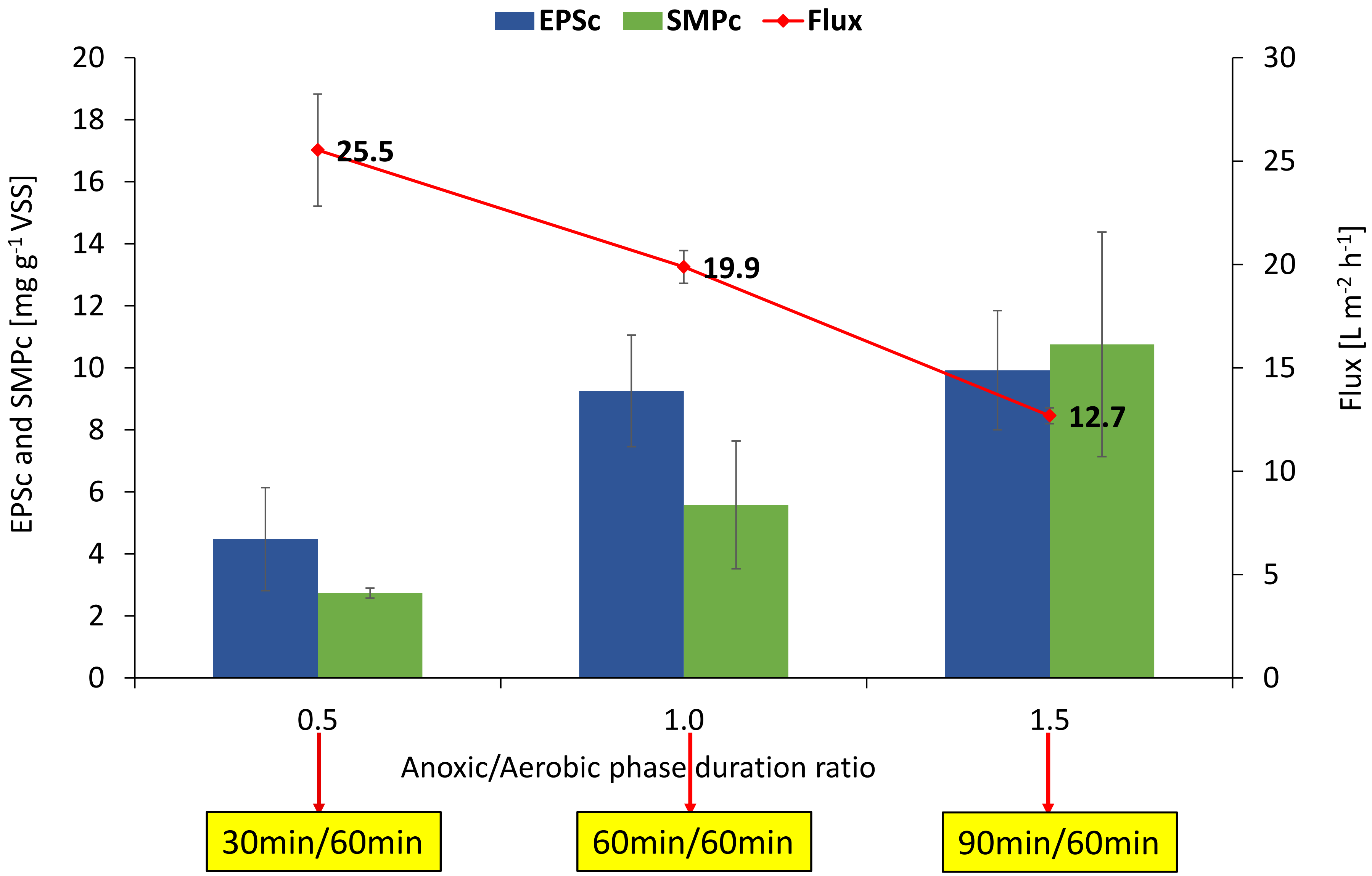
$$R = \frac{TMP}{J \times n}$$



SMP concentration was greatly affected at high F/M ratio (glycerol addition), resulting in membrane resistance.

EPSc, SMPc and permeate flux at various anoxic/aerobic phase duration ratios

Results



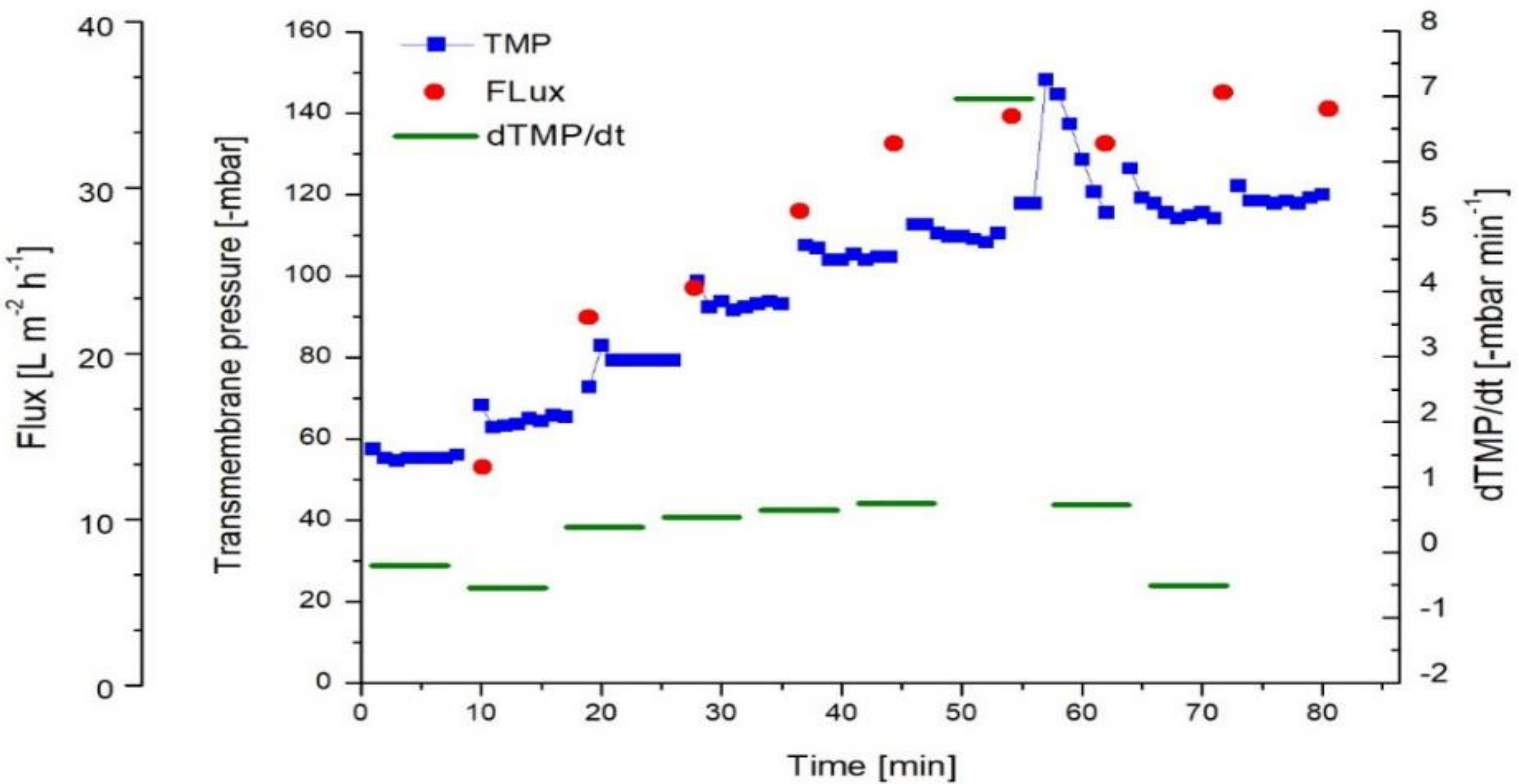
30min/60min

60min/60min

90min/60min

Results

Critical flux evaluation by dTMP/dt determination



flux-step method

critical flux: 32.6 L m^{-2} h^{-1}

dTMP/dt jump from 0.75 to 6.96 mbar min^{-1}

The dTMP/dt was found to be a suitable indicator of critical flux, since a sharp increase in its value was observed at the critical flux

Effluent parameters comparison (IAF-AS vs IF-MBR system)

Results

	IAF-MBR system		IAF-AS system		IAF-MBR improvement
Parameters	Average	St. Deviation	Average	St. Deviation	(%)
BOD_5 (mg L^{-1})	3.4	1.5	12.7	4.6	73
COD (mg L^{-1})	17.6	1.54	49.2	14.6	64
NH_4^+-N (mg L^{-1})	1.03	0.31	2.43	1.0	58
TKN (mg L^{-1})	6.76	1.39	8.27	2.2	18
NO_3^--N (mg L^{-1})	0.48	0.52	0.7	0.5	31
PO_4^{3-} (mg L^{-1})	0.21	0.1	0.72	0.25	71
SS (mg L^{-1})	0	0	21	3.17	100
Energy saving (%)	33		34		
Cost (€ m^{-3} d^{-1})	0.3-0.8		0.3-0.5		

Control of biological processes in IAF-MBR system

Correlation between pH/NH_4^+-N and ORP/NO_3^--N for aeration and anoxic phase control

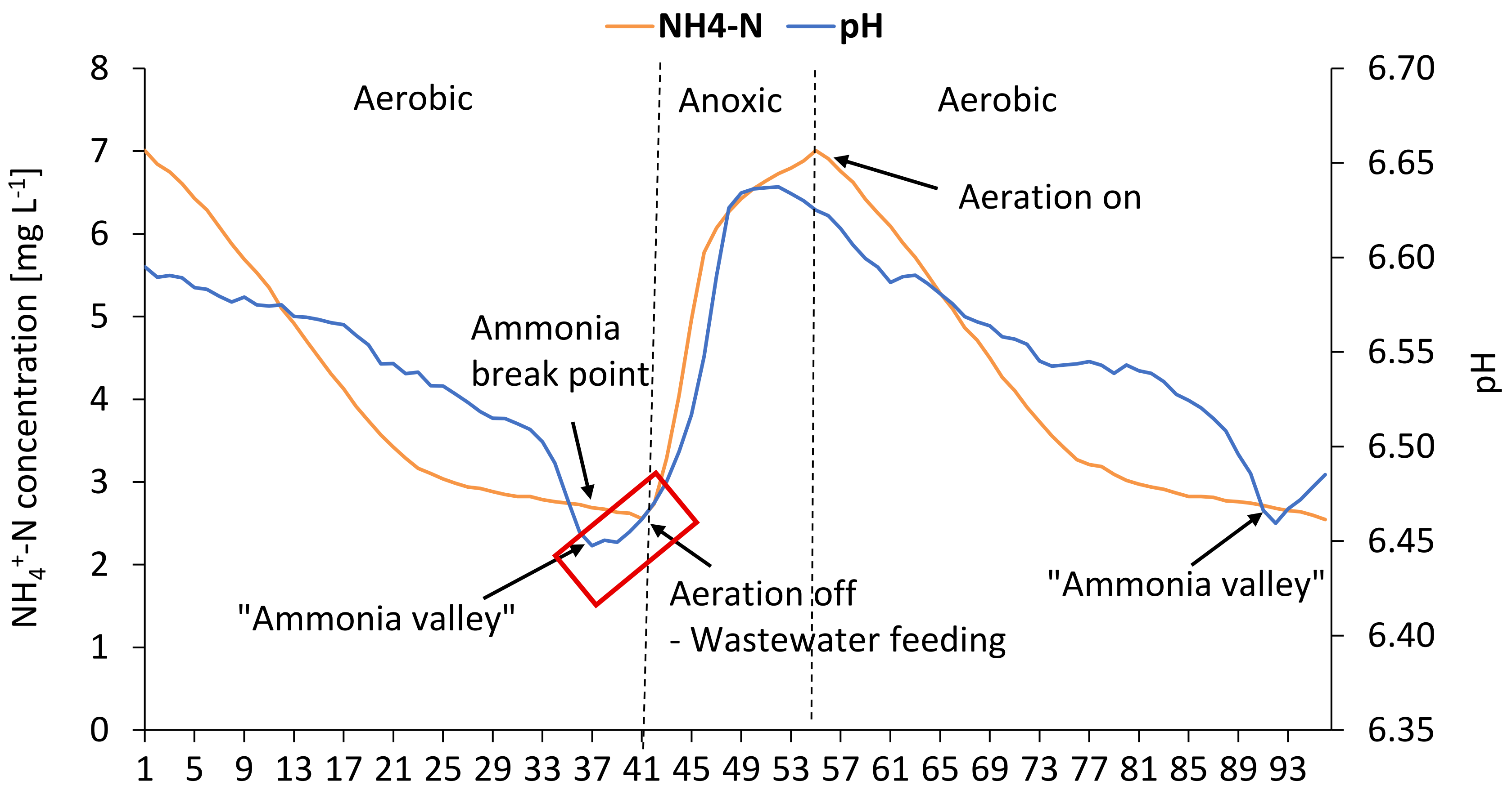
Inflection points detection

- For the anoxic period, through **“nitrate knee’’** detection using ORP profile, corresponding to the end of nitrate concentration and the anoxic period.
- For the aerobic period, through **“ammonia valley”** detection using pH profile, corresponding to the end of ammonia concentration and the aeration period.
- The dpH/dt and dORP/dt first derivatives were used as control parameters to detect ammonia and nitrates depletion.

$$\boxed{dpH/dt = 0 \ \ \& \ \ dORP/dt = 0}$$

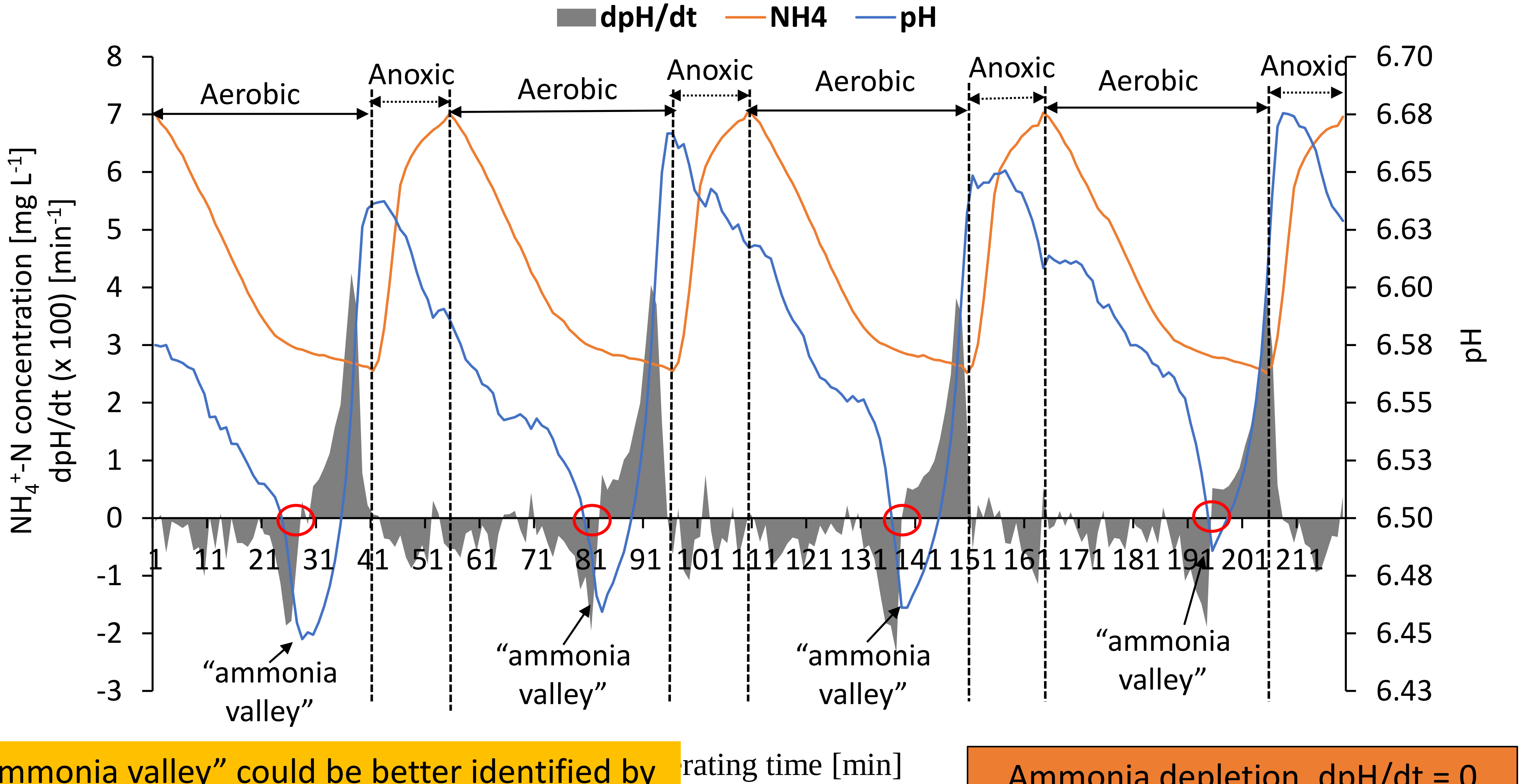
NH_4^+-N and pH profiles during successive aerobic/anoxic phases

Results



pH was successively decreased during nitrification process
pH increase was observed at the end of the aerobic phase, due to the ammonium depletion and the CO_2 stripping occurred

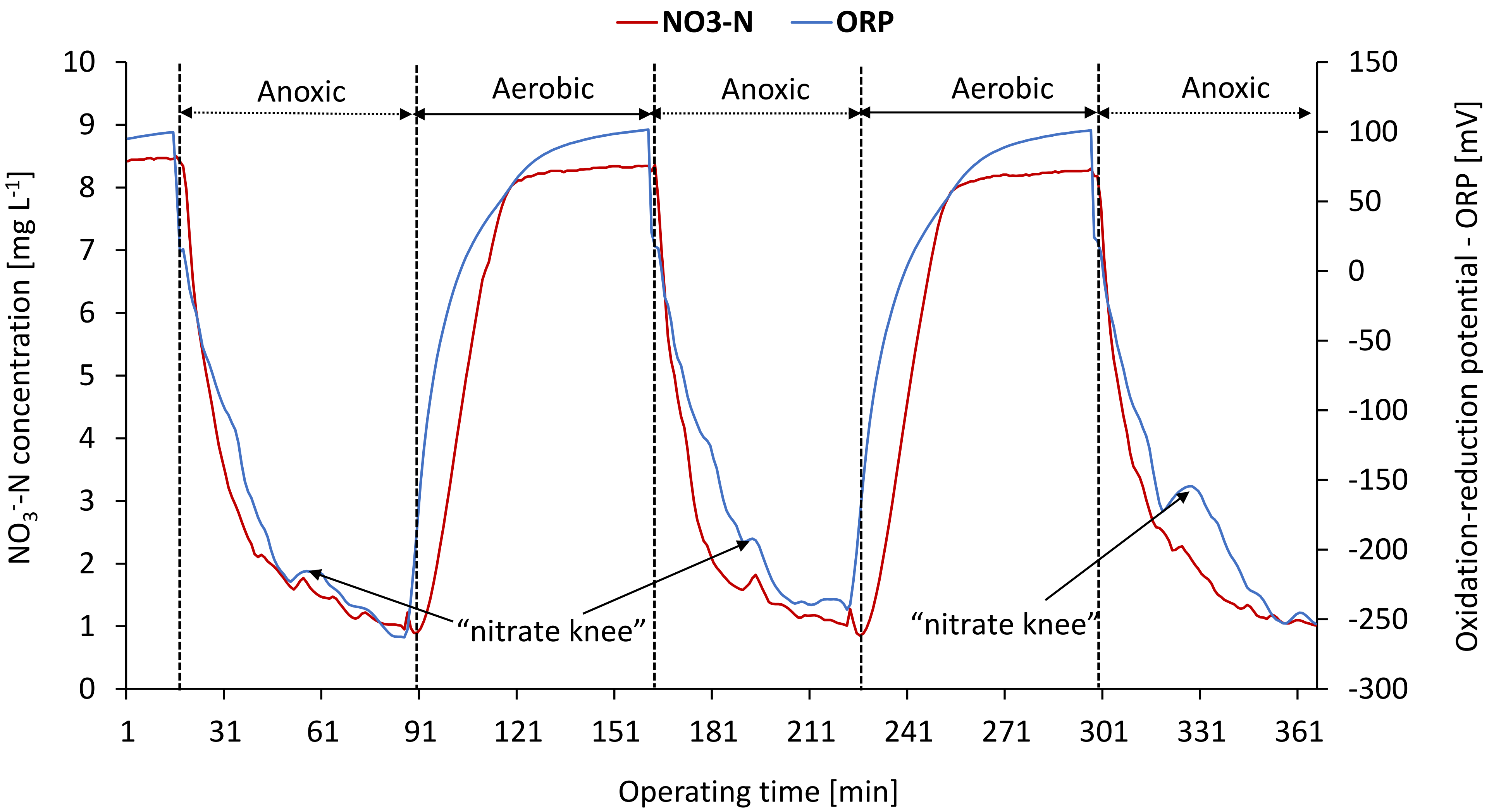
pH, dpH/dt, NH_4^+-N profiles and their inflection points



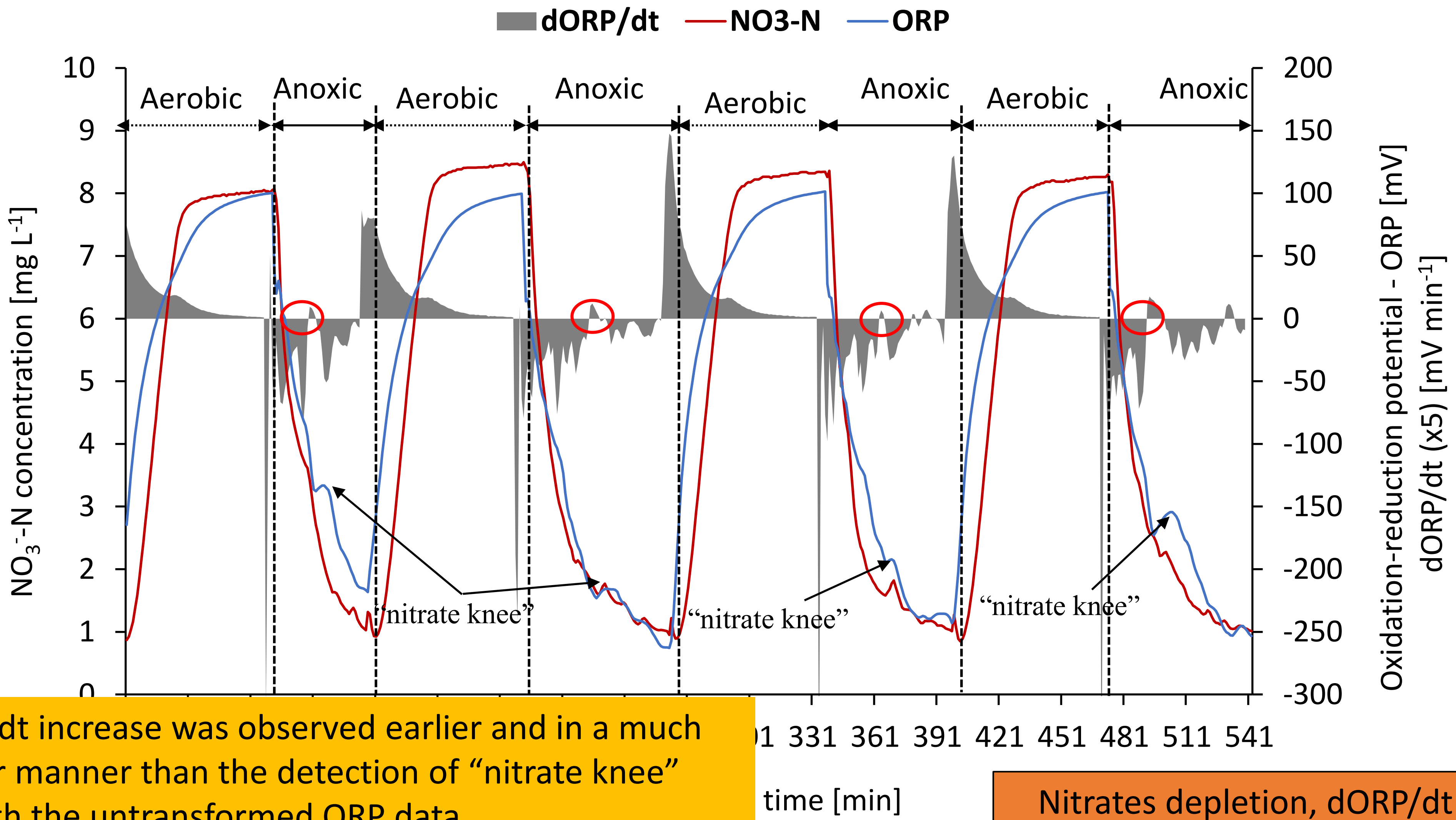
The "ammonia valley" could be better identified by the calculation of the pH first order derivative

Ammonia depletion, dpH/dt = 0

ORP and NO_3^--N profiles during successive anoxic/aerobic cycles



ORP, dORP/dt, NO_3^--N profiles and their inflection points



dORP/dt increase was observed earlier and in a much clearer manner than the detection of “nitrate knee” through the untransformed ORP data

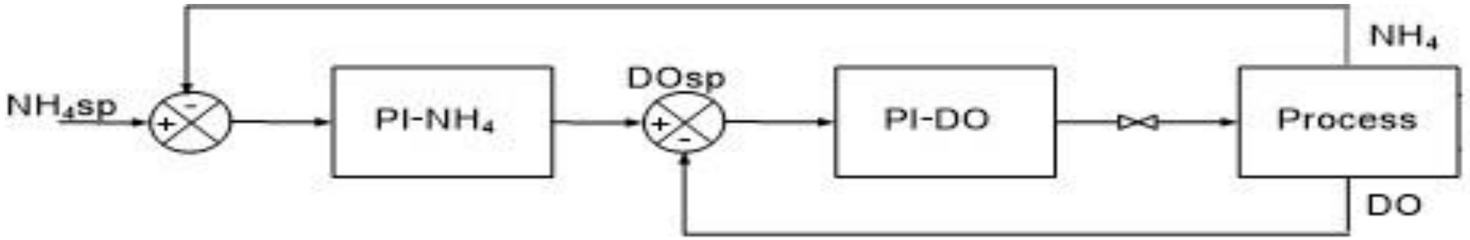
Nitrates depletion, dORP/dt = 0

Cascade DO control for nitrification process

NH_4/DO cascade control strategy

Results

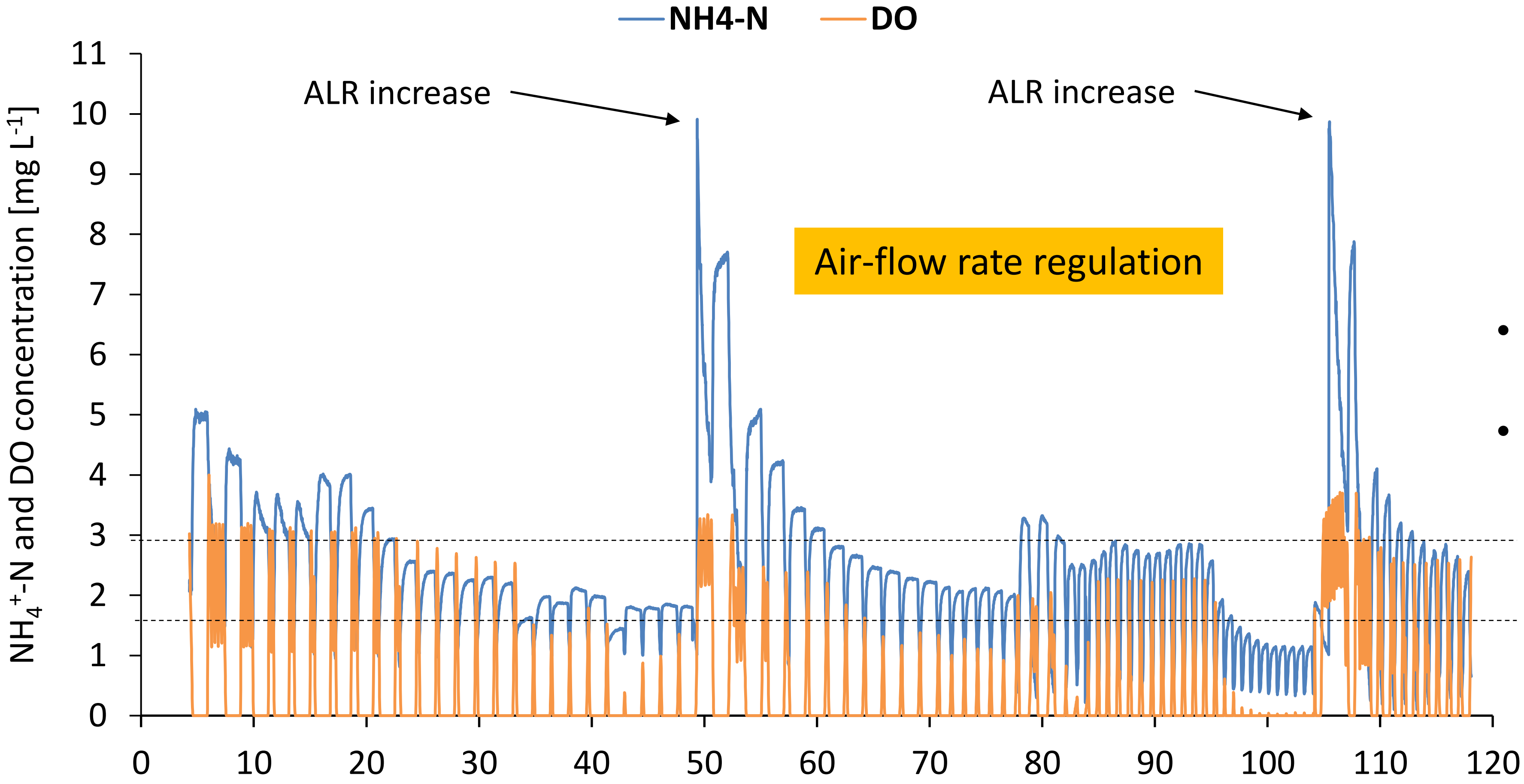
Control-loop of cascade control process



- PI-NH_4 → Primary controller
- PI-DO → Secondary controller
- NH_4sp: Ammonium-N set point → 3-4 mg L^{-1}
- DOsp: The input DO set point in the PI-DO
- air flow electro-valve regulation

Performance of cascade control

Results



ALR increase

ALR increase

Air-flow rate regulation

DOsp ≤ 3 mg L^{-1}

DOsp ≥ 1.5 mg L^{-1}

- NH$_4^+$-N , 1 ± 0.6 mg L^{-1}
- TKN, 4.7 ± 3.3 mg L^{-1}

The nitrification process was optimized meaning maximizing the ammonium-N removal at the lowest possible operational cost.

Controlled DO level in the region of 1.5 -3 mg L^{-1}

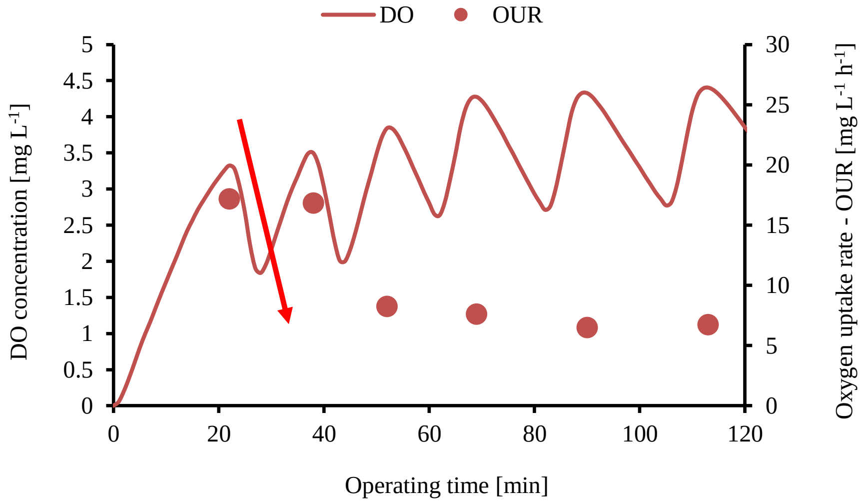
Aeration control by OUR biosensor

Aerobic phase length control through oxygen uptake rate (OUR)

OUR was calculated from DO depletion when the air-valve was switched off by applying aeration cascade control during the nitrification process.

OUR calculation was based on the following equation:

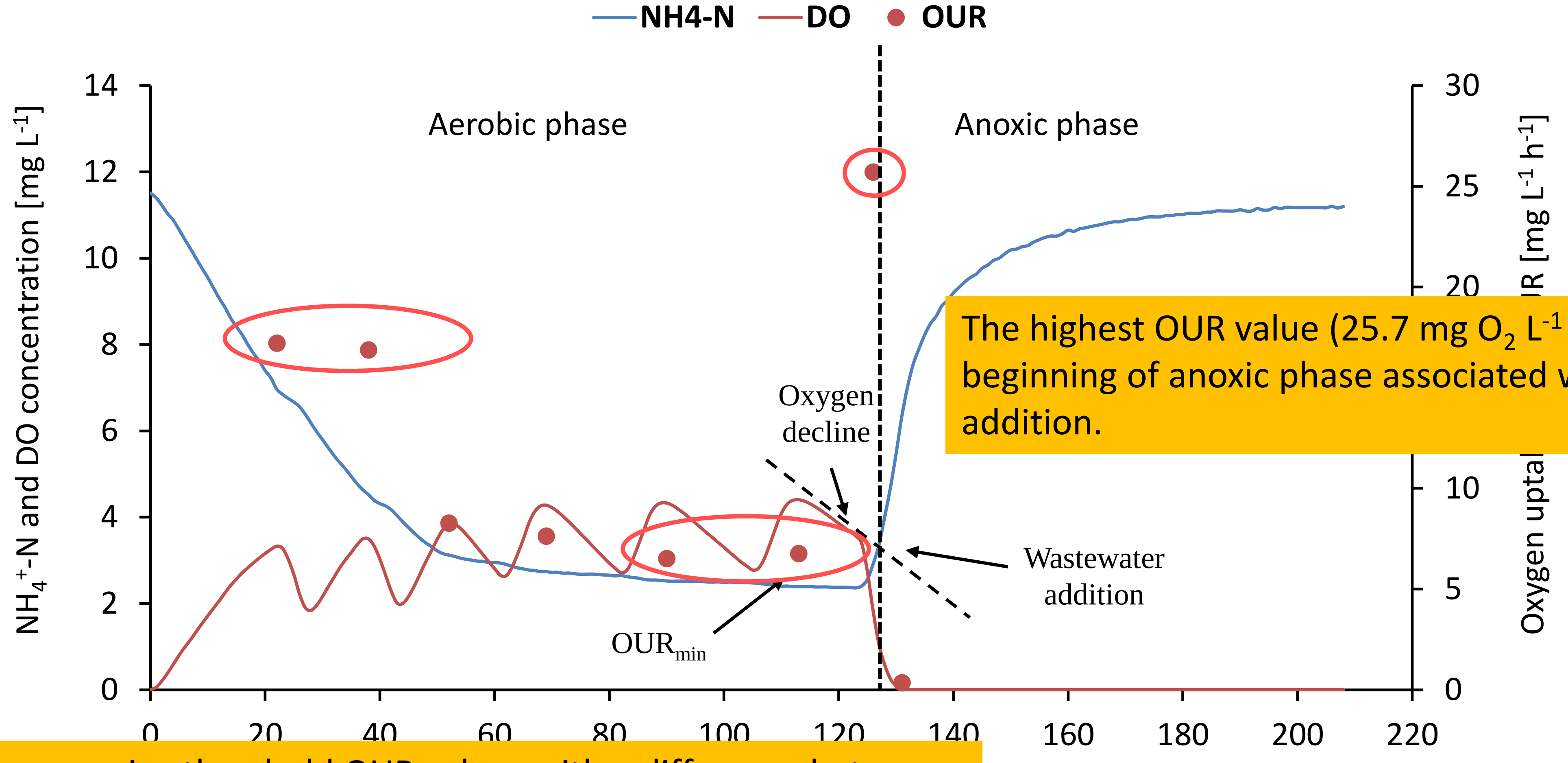
$$OUR = \frac{DO_0 - DO_i}{t_0 - t_i}$$



where DO_0 the highest DO value before air-supply switched off (mg L^{-1}), DO_i is the lowest DO value at the end of the non-aeration period (mg L^{-1}) and t_0, t_i corresponds to initial and end-time (min).

NH_4^+-N , OUR and DO profiles during a typical operating cycle

High OUR values are due to readily biodegradable COD (rbCOD) and ammonia oxidation at aeration initiation



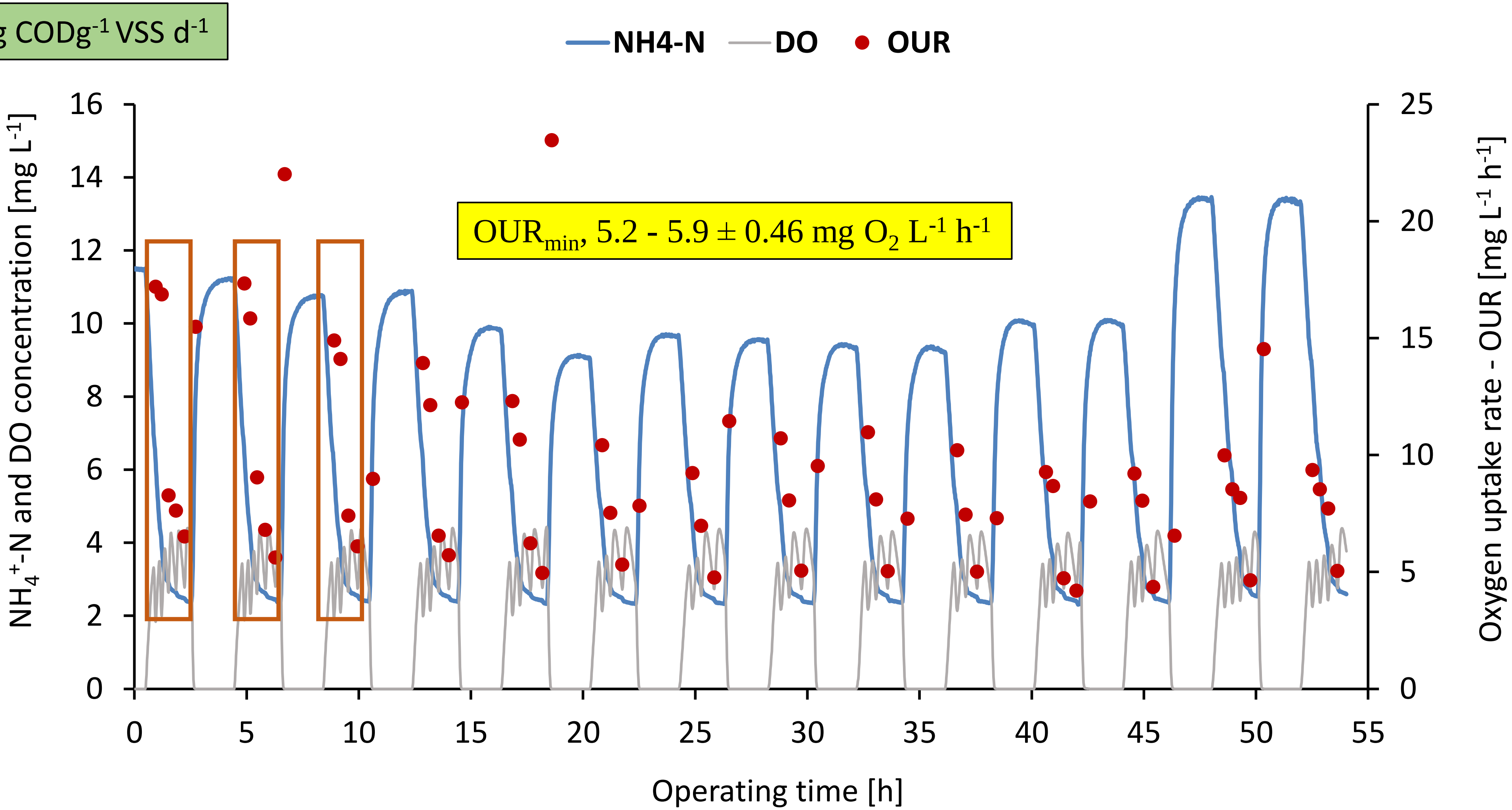
The highest OUR value (25.7 mg O_2 L^{-1} h^{-1}) at the beginning of anoxic phase associated with sewage addition.

Two successive threshold OUR values with a difference between them less than 1 mg O_2 L^{-1} h^{-1} indicate the end of nitrification

Monitoring of NH_4^+-N , OUR and DO profiles during alternating anoxic/aerobic cycles

Results

F/M, 0.2 g $CODg^{-1}$ VSS d^{-1}

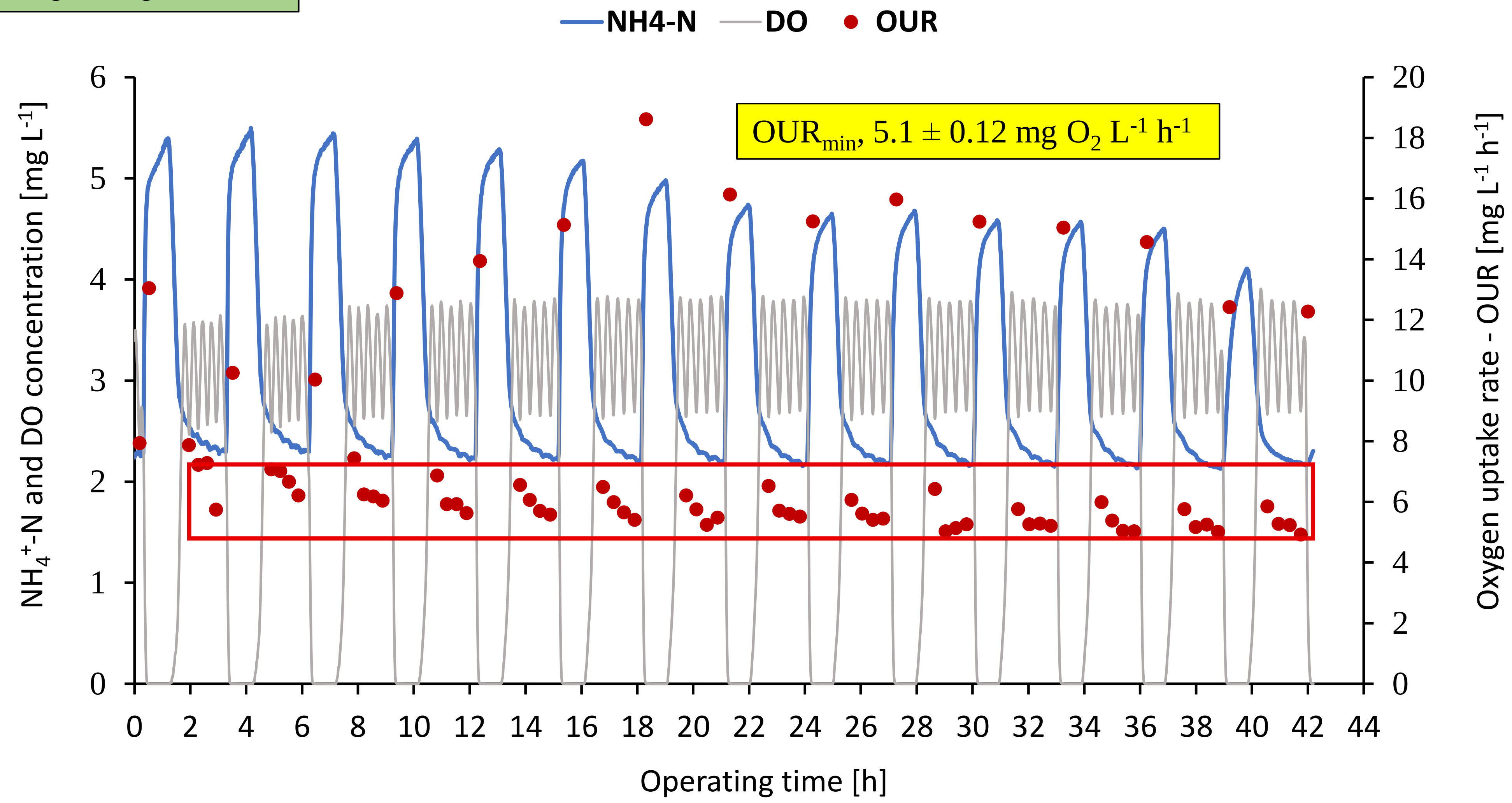


The OUR level was both affected by organic and ammonium nitrogen content

Monitoring of NH_4^+-N , OUR and DO profiles during alternating anoxic/aerobic cycles in low ammonium-N loads

Results

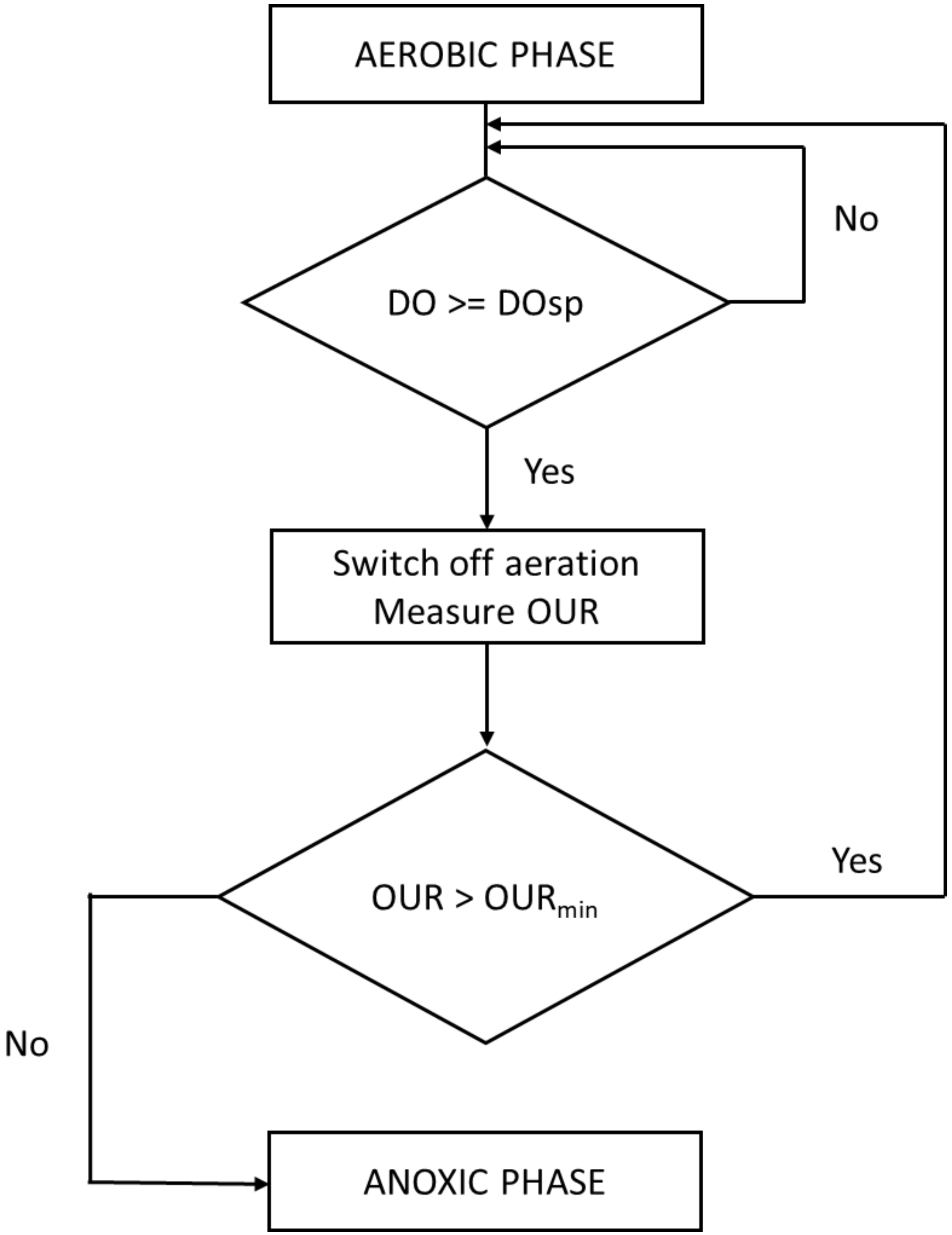
F/M, 0.11 g COD g^{-1} VSS d^{-1}



The OUR level was both affected by organic and ammonium nitrogen content

Results

Dynamic aerobic phase control by OUR biosensor



DO_{sp}, 3 mg L^{-1}

OUR_{min}, 5.5 mg O_2 L^{-1} h^{-1}

Conclusions

Positive impacts of implemented ICA (1/2)

- ✓ Optimization of control parameters in activated sludge systems.
- ✓ The *in-situ* ammonium-N, pH, nitrate-N and ORP sensors eliminates internal and external disturbances.
- ✓ Optimal control adjustment of nitrification and denitrification cycle period lengths.
- ✓ Intermittently aerated and fed (IAF) activated sludge systems improve the biological processes and minimize the operational costs.
- ✓ A novel membrane bioreactor achieves excellent effluent quality.
- ✓dpH/dt and dORP/dt first derivatives can be used to develop a control strategy around the identification of the completion of nitrification and denitrification.
- ✓OUR biosensor can be successfully used to supervise dynamically the aeration period.

Conclusions

Positive impacts of implemented ICA (2/2)

✓ Benefits of cascade control:

- Controlled DO level in the region of 1.5-3 mg L^{-1} secured the complete oxidation of ammonium nitrogen and the total nitrogen removal improvement.
- Energy savings are achieved through aeration reduction.

Filtration process in MBR operation

Conclusions

- ✓ Online TMP monitoring is an effective tool to detect the membrane fouling grade in order to apply the appropriate cleaning method.
- ✓ The most optimal cleaning method was suggested to be a suitable combination of both backwash flow and air-flow rate in a long-term to face reversible fouling problems.
- ✓ Regarding irreversible fouling, extensive chemical cleaning with NaOCl and citric acid solution can restore membrane efficiency.
- ✓ The anoxic/aerobic phase duration ratio increase led to elevated membrane fouling rate under intermittent aeration and feeding conditions.

Novelty

Novelty

- Optimization in process control of an intermittently aerated and fed (IAF) activated sludge system was performed, applying real time control strategy, using *in-situ* ion selective electrodes (ISE) NH_4^+-N and NO_3^--N sensors.
- pH, oxidation-reduction potential (ORP) sensors and Oxygen Uptake Rate biosensor were proved to be effective in order to control nitrification and denitrification processes.
- For the first time air flow rate was controlled by an ammonium-based cascade modification.
- For the first time an integrated, sophisticated control system was developed to supervise and control simultaneously both biological nutrient removal processes, membrane fouling and filtration process applied in an IAF-MBR system.

Literature

Literature

- ✓ Azis, K.; Ntougias, S.; Melidis, P. (2021). NH_4^+-N versus pH and ORP versus NO_3^--N sensors during on-line monitoring of an intermittently aerated and fed membrane bioreactor. *Environmental Science and Pollution Research*, **28**(26), 33837 - 33843.
- ✓ Azis, K.; Ntougias, S.; Melidis, P. (2019). Fouling control, using various cleaning methods, applied on an MBR system through continuous TMP monitoring. *Desalination and Water Treatment*, **167**, 343-350.
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